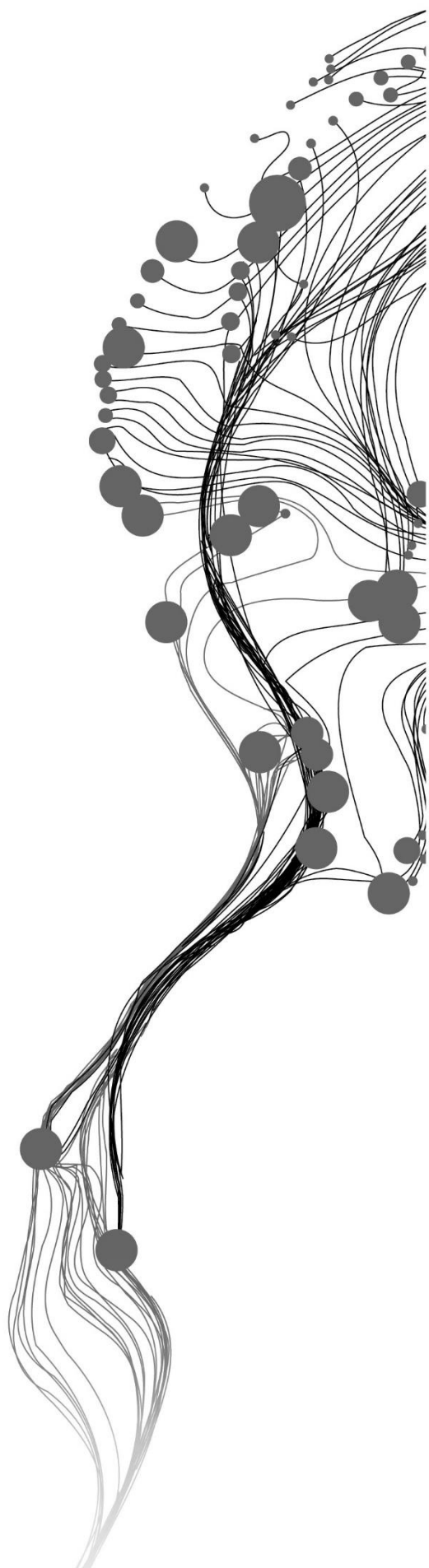


USING AGENT-BASED MODELING FOR HURRICANE SHELTER PLANNING IN DOMINICA

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September 2018

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Cartography M.Sc.

Using agent-based modeling for hurricane shelter planning in Dominica

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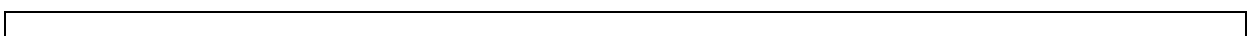
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ABSTRACT

The Caribbean island of Dominica is at constant risk of being hit by tropical storms during the hurricane season. As hurricane Maria in September 2017 revealed, the consequences can be disastrous. Therefore, Dominica and areas in similar situations need to raise their resilience to natural risks. This is intensified by the potential consequences of climate change. The application of agent-based modeling can be used for the simulation of hurricane events, including the simulation of the evacuation.

In this thesis, an agent-based model prototype was developed, simulating the movement of evacuees in an evacuation event. The particular about the model concept is the integration of a multi-event scenario, modeling two storms in one season. Using this approach, the influence of damages done to infrastructure to movement patterns and shelter allocations of evacuees were examined. Additionally, a focus was laid on a critical interface design of the model application and visualization of the results.

It was observed, that the models' concept approach can be useful for analyzing effects of road damages. Being able to identify critical road segments and shelter locations can help responsible authorities to take actions for vulnerability reduction and resilience raising. Furthermore, using a thoughtful interface design and visualization concept, can improve the understanding and communication of the model.

However, many simplifications in the model concept may need to be reduced to develop the prototype further and achieve more valuable results. The functionality of the interface and visualization needs further research and consideration. Additionally, the integration of the potential user into the research and development process must be intensified.

Keywords: agent-based modeling- hurricane evacuation simulation - multi-event scenario - disaster risk reduction – shelter planning - geospatial visualization

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1. INTRODUCTION

1.1. Problem Statement

Natural hazards like tropical storms and hurricanes pose a permanent risk to many regions and their population. They can cause the direct threat of life, destruction of homes and basis of life, breakdown of the economy or outbreak in the aftermath and more. Depending on the location, the exposure of a population towards natural hazards varies, as well as the preparedness of a society, the resilience, towards a potential catastrophe is different (Lam et al. 2014). Small island states in the Caribbean are exposed to natural risk, especially to those caused meteorologically, such as tropical cyclones and their strongest category: hurricanes. In addition to this, many states in the Caribbean have limited resources and are vulnerable, yet not resilient to the impacts of those risks (Jetten et al. 2014).

The Atlantic Hurricane season of 2017 was a devastating one. Seventeen named storms affected Central America and the South-Eastern States of the USA (Shultz et al. 2018). Among those storms, ten developed into hurricanes. Hurricane Maria was a category five hurricane, passing directly over the island of Dominica, and affecting other islands as well. Being hit directly by the hurricane, the destructions on Dominica were disastrous. Thirty-one people died during the event and a considerable bigger number of people were injured severely (ACAPS 2018). Houses were destroyed, as was the majority of the island's infrastructure. Apart from the direct damage due to the wind, the massive rain falls combined with the steep terrain of the island led to landslides. The storm surge led to damage, as did the flooding of the rivers. After the hurricane passed, the island was barely recognizable, and thousands of people lost their homes and basis of life. While this event alone revealed the danger the people of Dominica are exposed to, the effects of climate change might lead to more severe tropical cyclones and hurricanes in future (Lam et al. 2014), and an increase of the number of events per season (IPCC 2014).

To make life in Dominica possible now and for future generations, it is necessary to increase the islands preparedness and resilience. This is supported by an ongoing shift from an ex-post response and recovery to an ex-ante approach with a focus on minimizing the disaster risk by reduction of vulnerability, capacity building, better information and institutional strengthening. The planning and organization of shelters and evacuation routes in case of emergency are crucial (World Bank 2012). To optimize shelter and route planning, assumptions of the population's behavior and their resulting movement in case of evacuation is needed. In addition to this, it must be taken into consideration that damage to infrastructure as a consequence of such an event might affect the evacuation of the following storm event.

Due to the impacts of climate change, it is not unlikely, that in future multiple events occur in one season, affecting the same island. Roads and bridges, previously designed to be part of an evacuation route, may be

impassable and the recovery time between storms might not be sufficient to allow for reconstruction. The planning authorities and other responsible bodies need to be aware of these circumstances.

Having limited resources and capacities, the island of Dominica and its authorities need methods to be developed to help to raise resilience to catastrophes (Lam et al. 2014). Agent-based modeling may be used for simulations of such events and generate valuable information. This could, for example, relate to the movement of population in the case of evacuation (Chen et al. 2006). Such a system may also be beneficial for running different “What if...?”-scenarios, allowing the authorities to be better prepared, and thus resilient to natural disasters.

This master thesis uses agent-based modeling to create a prototype of an evacuation simulation application to be used to evaluate shelter locations and evacuation routes, integrating a multi-event scenario and the corresponding damages to infrastructure. A visualization of the results, taking the potential audience into account, will be performed and suggestion for future improvements will be made. Not only visualization of the results, the model’s output, but the interface design will be discussed in this context.

Following the Introduction chapter, the second chapter gives an overview over the theoretical background and current research on the topic. Subsequently, the study area and the data used in this study are described in chapter three. In chapter four the methodology is depicted and follow by the results in chapter five. The results of the thesis are discussed and put in context in chapter six, which is followed by the closing conclusion with recommendations for future work.

1.2. Research Identification

The main objective of the thesis is to develop a system that facilitates the combined analysis of infrastructure disturbances, especially road damages, and evacuation behavior for planning purposes. It can be split into the following sub-objectives:

- Creation of a model that integrates both, infrastructure disturbances and people’s behavior in an evacuation event
- Critical evaluation of the visualization of the model outcome addressing the specific needs of evacuation planners

The first sub-objective will lead to the creation of a prototype of an agent-based model for hurricane evacuation for Dominica, to evaluate multi-event scenarios. Potential audience for the result of the research are decision makers and stakeholder in Dominica, as well as planning authorities in Dominica. Additionally, (International) aid organizations, other researchers interested in the field of study, and the Dominican public for raising awareness to natural disasters might benefit from the findings. Depending on the addressed audience, different visualization techniques may be suitable. A critical evaluation of the possible

visualizations within the used software's capabilities, as well as of the model output will be conducted to provide recommendations for useful visualizations for potential users.

From the main objective and the sub-objectives, different research questions arise, which need to be answered during the thesis result. The overall question to be answered is connected to the main objectives: How can agent-based modeling with an integration of a multi-event scenario be used to improve preparedness to hurricanes in Dominica?

Further questions can be subdivided into groups, linked to the sub-objectives:

Sub-objective 1: Model creation

- Is it possible to find an existing model or implementation logic for evacuation modeling that can be integrated in the model prototype?
- How should the movement of agents prior, during and directly after a hurricane hit be modeled?
- How can damage to infrastructure be integrated into the evacuation model?
- How can multiple sequential hurricane events be simulated?
- What output can be created with the model?

Sub-objective 2: Communication and visualization

- What output visualizations are feasible within the used NetLogo software and what visualizations can be performed with additional software, such as GIS, using the created output of the model?
- What output visualization is needed to evaluate the different stages of a hurricane event and the evacuation?
- How can a potential user (e.g. planner) use this tool to assess the situation and improve the preparedness?
- Are multiple visualizations and visualization techniques possible and purposeful?

The integration of a multi-event evacuation simulation in an agent-based model context provides an innovative approach in the field of evacuation simulation, as it integrates the dynamic nature of a hurricane event and the damages done to infrastructure. Damaged infrastructure will subsequently lead to changes in the behavior of the population and a model incorporating these changes may reflect the behavior appropriately.

In addition to this, the model needs to be set up accordingly to on the one hand simulate the system sufficiently and on the other hand be simple enough to be used by non-expert users. The compilation of the workflow in the context of evacuation route and shelter planning, together with the visualization of the results of the model, including interface design and cartographic considerations, provide an overall innovative character to the research topic and approach.

2. LITERATURE REVIEW

The following chapter intends to give an overview of the theoretical background of the study's content. Covering brief introductions of the basics and current relevant research, the chapter is divided into three thematic subchapters.

2.1. Emergency and evacuation modeling

The function of a model is to purposefully represent a real-world system to solve problems or answer questions about the system. The model's purpose is crucial in this context. The real-world system is simplified and reduced using equations or computer programs in a way, that manipulations and experiments can be performed on it. Depending on the purpose, irrelevant elements and aspects of the real system are neglected and only those components important for answering the question are modeled (Railsback and Grimm 2012).

The general purpose of models connected to spatial context is to answer "What if...?"-questions in connection to planning and prediction activities (Kraak and Ormeling 2015). In the context of disaster management, planners may use findings of these predictions to adapt their preparation efforts and focus on relevant and efficient improvements. For emergency planning, having information about the time required for evacuations from various places under different conditions can be crucial to prepare for such events (Izquierdo et al. 2009). Modeling the potential flow of evacuees additionally allows to plan evacuation routes, as well as shelter locations and allocations (Chen et al. 2006).

Different modeling techniques can be used to model evacuations. One of the most common forms of scientific modeling is the equation form or equation-based modeling. An equation is set up, trying to describe the system as a whole (Wilensky and Rand 2015). Borshchev and Filippov (2004) distinguish between three paradigms in simulation modeling: System dynamics, discrete events and agent-based modeling. Within these paradigms different approaches are possible. In their study, Zheng et al. (2009) present and compare seven methodological approaches for crowd evacuation of buildings: cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models and approaches based on experiments with animals.

With many approaches available and their distinction and classification dependent on the source and varying perspectives, the choice of the right method or method combination, depending on the context and purpose, is an important step of each modeling study. The agent-based modeling technique in the context of evacuation modeling will be described in the next paragraph.

2.2. Agent-based modeling for evacuation modeling

The concept of agent-based modeling tries to simulate a system by representing its individual components and behaviors. In agent-based models, “individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally” (Railsback and Grimm 2012, p. 10). Thereby it can be analyzed how the system’s behavior is constituted by the characteristics and behaviors of its individual components. Following Bonabeau (2002), agent-based modeling is more a mindset than a technology. “The ABM mindset consists of describing a system from the perspective of its constituent units” (Bonabeau 2002, p. 7280). Additionally, the author states, that agent-based modeling should not be seen as an alternative for or opposing to equation models. Rather, it can be described as “a set of differential equations, each describing the dynamics of one of the system’s constituent units” (Bonabeau 2002, p. 7280).

To approach an agent-based model conceptually and to describe its functionality in a standardized way, the ODD (Overview, Design concepts, Details) protocol is frequently used. By following the descriptions of a set of properties for a model, it allows an easier way to both write and read model formulations (Railsback and Grimm 2012).

Considering emergency and evacuation modeling, the typical agents to be modeled are the evacuees. They react to a threatening situation and move in space, with a certain defined behavior. The model’s environment usually describes a representation of the real-world landscape, in which the threatening situation is taking place and towards which the evacuees (agents) are reacting to (Wilensky and Rand 2015). Agent-based model-based applications can support timely and enhanced data acquisition, information production, decision support, and action coordination. They can be used to support many processes within the phases of the disaster management cycle from mitigation and preparation to response and recovery (Fiedrich and Burghardt 2007).

Within the agent-based modeling technology, different techniques exist to model evacuation events or other comparable phenomena based on movement or flows: raster-based (see Wąs and Kulakowski 2010), network-based (see Usman et al. 2017) or learning algorithm-based models (see Abdulkareem et al. 2017). For the first, values in a raster grid are used by to calculate a least cost path, which the agents may follow in their movement. The second uses a network, for example a road network, and values of the edges to calculate a path along the network. Learning algorithms can be used in a model context, to make agents learn while they are acting and interacting, adapting their behavior to experiences and surroundings.

Overall, there has been extensive research in the field of agent-based modeling in evacuation context. Chen et al. (2006) created a model for hurricane evacuation in the Florida Keys. The focus was put on the clearance time of the entire area and on how many residents would need accommodation once the route became impassable. Liu and Lim (2016) performed a model simulation for the 2011 Brisbane flood, concentrating their research on shelter assignment and routing strategy and thereby integrating GIS-based spatial analysis.

Focusing on the interactions among evacuees during an evacuation process, Zhang et al. (2009) analyzed how different behaviors of agents during the process may change the overall movement in the network. What most of the studies share is that they either focus on motorized traffic simulation or on building or urban (public places / events) evacuation. Compared to former-mentioned studies, the thesis will differ in the way, that it is not possible to clear the affected area and most people evacuate via walking. Being a Caribbean island, Dominica is cut off once the hurricane hits the island. Furthermore, the model will neither be based on motorized traffic nor will it include building evacuation components. The inclusion of infrastructure disturbances in a multi-event scenario (two events in one season) is another point, which makes the study deviate from the former-mentioned.

2.3. Visualization of simulation results

Evacuation models deal with representations of real-world elements. Therefore, a brief introduction of the visualization of geographic and cartographic elements will be given in this subchapter. This visualization may be done during the simulation as an integrated part of the software and its interface or as a presentation of the resulting model output. Whereas the visualization during a simulation run can be described as an animation, displaying dynamic entities moving in space, the output data, which can be integrated in a GIS is of static nature. For example, a raster output of a model may hold values in each pixel, counting agents that were located on it.

In a visualization and design context, points, lines and area marks constitute the primitives building blocks, called basic graphic elements (Robinson et al. 1995). Primary visual variables can be used to make these graphic elements on the map more or less distinctive and prominent. Following the definition of Bertin and Berg (2011) (first introduced 1967 by Jacques Bertin), these variables are: shape, size, orientation, hue (color), value (color) and chroma (color). Additionally secondary visual variables (pattern arrangements) are feasible: texture, arrangement and orientation (as pattern) (Robinson et al. 1995). Using these variables, objects can be visualized based on their attributes and to allow distinction between different types of objects, as described by White (2017). An overview of potential usage of these variables can be found in figure 2.1.

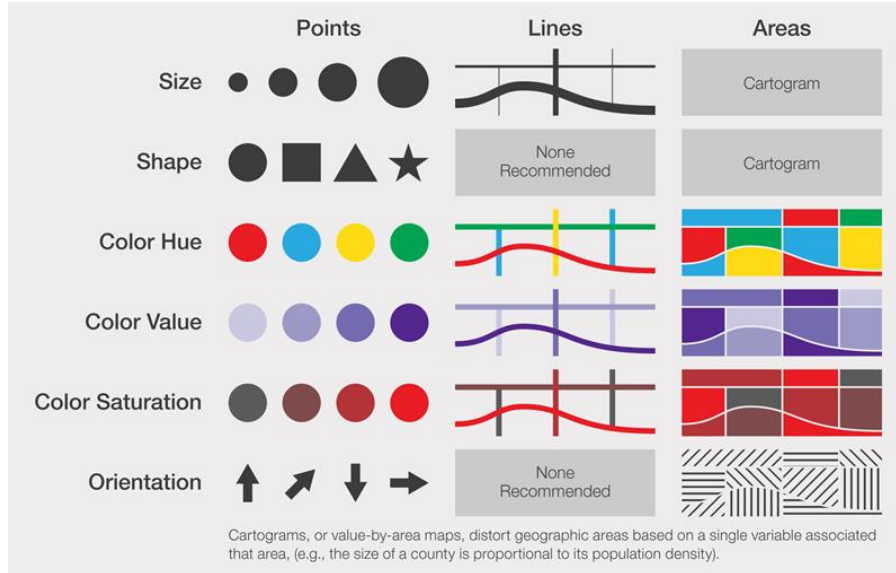


Figure 2.1: Common visual variables for point, line and area phenomena (White 2017)

In the end, the purpose of the (geo)visualization is to be used by specific users. The design, basically the arrangement of different graphic elements and corresponding visual variables, need to be tailored to the user's need (van Elzakker 2004). Additionally, depending on the software, the model may allow direct user interaction with the software specific interface options. Marinilli (2002) defines a number of general principles for basic interface design: know your user, minimize the load on users, preserve consistency, ensure overall flexibility, error recovery and customization, follow standards and make the system internal state explicit. Cron et al. (2008) make suggestions for enhancing the usability of applications by sophisticated grouping of the functions in the graphical user interface (GUI).

Considering the visualization of agent-based models, Dorin and Geard (2014) point out the importance and benefits of the visualization, as they highly improve the understanding and communication of the model itself and its findings. In general, they come to the conclusion, that more thoughts on visualizations should be included in modelling related research. Kornhauser et al. (2009) provide a comprehensive and detailed list and design guidelines of possible visualizations in the frequently used agent-based modelling software Netlogo. Additionally, it needs to be mentioned that an agent-based model with its spatially and temporally dynamic functionality and output data can be approached from the perspective of the visualization of spatio-temporal data. Muller and Schumann (2004, c2003) provide a detailed overview of possible approaches for the visualization of time-series data, dynamic presentation techniques and event-based visualization.

3. STUDY AREA AND DATA DESCRIPTION

The following chapter will give a short introduction about the Commonwealth of Dominica and its capital Roseau, which was chosen as the study area for this thesis. A focus will be laid on the exposure towards tropical cyclones and the role of climate change. In another subchapter, the data used for the methodology will be described briefly and the data sources will be given. Additionally, any changes done to the original data are communicated.

3.1. Study area

The Commonwealth of Dominica is an island republic in the Lesser Antilles in the Caribbean Sea and part of the Windward Islands, with an area of about 750km². It is neighbored by Guadeloupe in the northwest and Martinique in the southeast (ACAPS 2017). Being an island of volcanic origin with nine live volcanoes, the landscape has high elevations in the center with steep terrain. The last official census of the Dominican government was performed in 2011 and states the population around 71,000 (Commonwealth of Dominica 2011). The United Nations World Population Prospect estimates a population of around 74,000 for 2017 (United Nations 2017). Due to the topography and the historical development of the island, the population is concentrated at the 91 miles coastline, as are most of the man-made structures and infrastructure (World Bank 2012). The capital of the country is the city Roseau at the coast of St. George parish in the southwest of the island. The formerly mentioned census of Dominica specifies the population of the capital at 14,725 persons (Commonwealth of Dominica 2011). The economy is highly dependent on agriculture and fishing but has had an increase in the tourism industry and service sectors since 2008 (Paul-Rolle 2014). In total, Dominica is a lower middle-income country and the poorest of the southeastern Caribbean islands (ACAPS 2017).

Located in the Caribbean, Dominica is highly prone to be affected by tropical storms and hurricanes. The probability of being hit by a hurricane is above 10% in any given year (ACAPS 2017). Additionally, the country experiences some of the highest annual rainfall amounts in the region, which is starkly influenced by orographic effects. The rainfall coupled with the island's steep terrain increases the risk of landslides and floods (World Bank 2012).

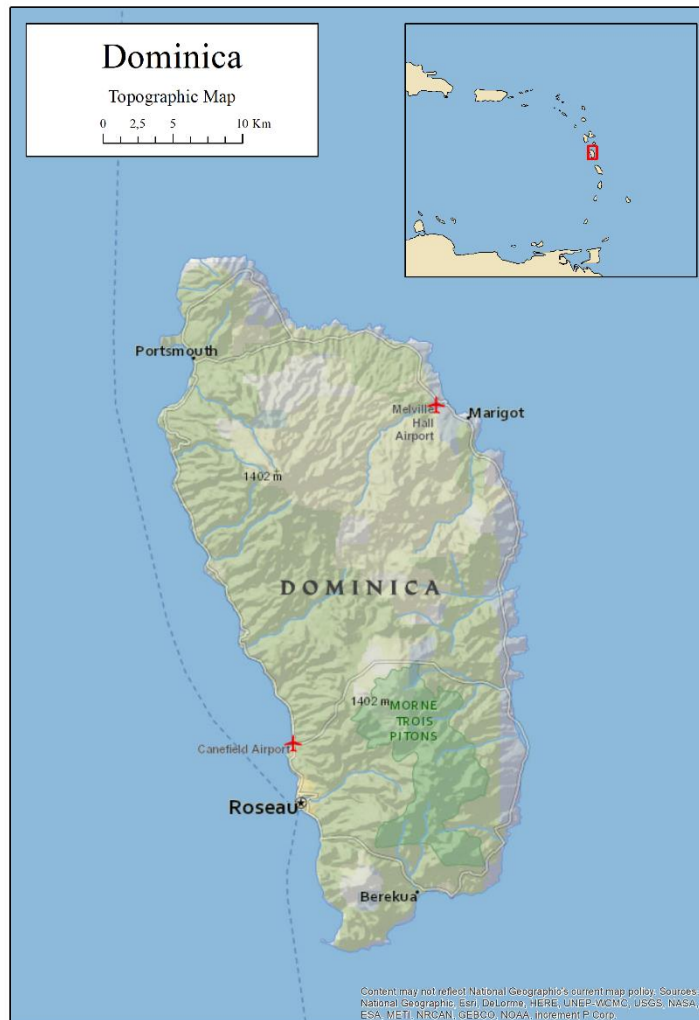


Figure 3.1: Topographic map of Dominica with indication of its location in the Caribbean.

From 1979 to 2012, Dominica was impacted by 15 tropical storm systems, including 11 hurricanes (World Bank 2012). On the 18th September 2017, Hurricane Maria, a Category 5 hurricane with 160 mph wind speed and higher gusts, directly passed over the island and revealed its vulnerability again. Thirty-one people were killed, 37 reported missing. In total 65,000 people (around 80% of the population) were directly affected. Around 90% of the roofs were damaged or destroyed, power and water supplies disrupted, and entire crops destroyed. Additionally, the infrastructure has been affected heavily. Damaged transformers and electrical generations sites led to at least 75% network going down. Telecommunication services were interrupted, cutting Dominica off from the outside world and disturbing communication within Dominica. Roads were covered by debris or destroyed by landslides, bridges washed away by flash floods (ACAPS 2018).

Similar disasters may be expected to strike Dominica more frequently in future. Climatological hazards are projected to change rapidly, in connection to climate change. The islands of the Caribbean will be affected in a drastic manner (Shultz et al. 2018). Tropical cyclones are likely to increase in magnitude and frequency

(IPCC 2014). Additionally, sea level rise caused by climate change is expected to make the hazard situation worse (Jetten et al. 2014).

The creation of a model prototype in this study will not take the entire island into account, but a large-scale area with more details (see figure 3.2). Certain criteria had to be met for the definition of the sub-area: relatively dense population and road coverage, multiple shelters, and potential damage to infrastructure. The capital of Dominica Roseau was a logical choice, meeting all criteria. More details about the study area will be given in the methodology chapter.

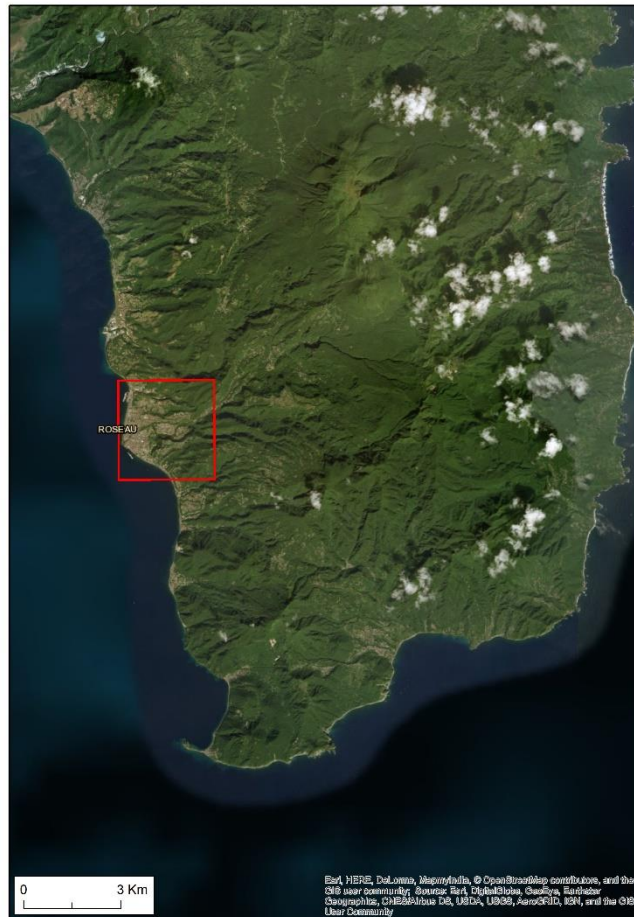


Figure 3.2: Indication of the study area extent of Roseau and surroundings in Southern Dominica

3.2. Data description

For the set-up and running of an evacuation simulation model, certain data and especially spatial data is needed. The data used in this study will be introduced briefly here and the data sources will be described. However, the specific use and the integration of the data into the model will be further explained in the Methodology chapter.

Road data is crucial for a model based on a street network (as will be explained later). Data about the location of buildings is also important. In this study, OpenStreetMap (OSM) data was used. The quality of OSM data, being a product of collaborative mapping, may sometimes be doubtful. However, for Dominica the Humanitarian OpenStreetMap Team (HOT) carried out a project for data improvement, reacting to the disaster caused by Hurricane Maria. As the focus of this project was to improve data of roads and buildings, by adjusting with recent satellite imagery, the quality in the context of positional accuracy (location of objects) and completeness (coverage of relevant objects) should be sufficient. However, the attribution, for example information about the road surface, has not been the main concern of the project. Thematic accuracy in the sense of detailed attribute information entries can therefore not be expected. OSM data can easily be downloaded via the QGIS software with the QuickOSM addon. The keys which must be given in the addon to load the correct dataset for roads and buildings are “highway” and “building”. The right spatial extent was defined by panning and zooming and thereby specifying the map extent in the QGIS software to the island of Dominica. The data was saved in shapefile format, which can be loaded into NetLogo.

Some minor edits to the data were performed. The street network is defined by vertices and edges. Vertices are transformed to nodes in NetLogo, edges to links between nodes. For the methodology of this study, it is advantageous to have a relatively high number of nodes, which will be explained in chapter four. Simple straight streets may be defined by two connected nodes only. Editing was performed on rather long segments without nodes, adding nodes in between without changing the general appearance of the street (see figure 3.3). A focus needed to be laid here especially on streets with many (potentially residential) buildings and shelters. The definition of a subarea as study area furthermore led to some dead-end streets close to the borders, which were deleted, as they might influence the model negatively otherwise.

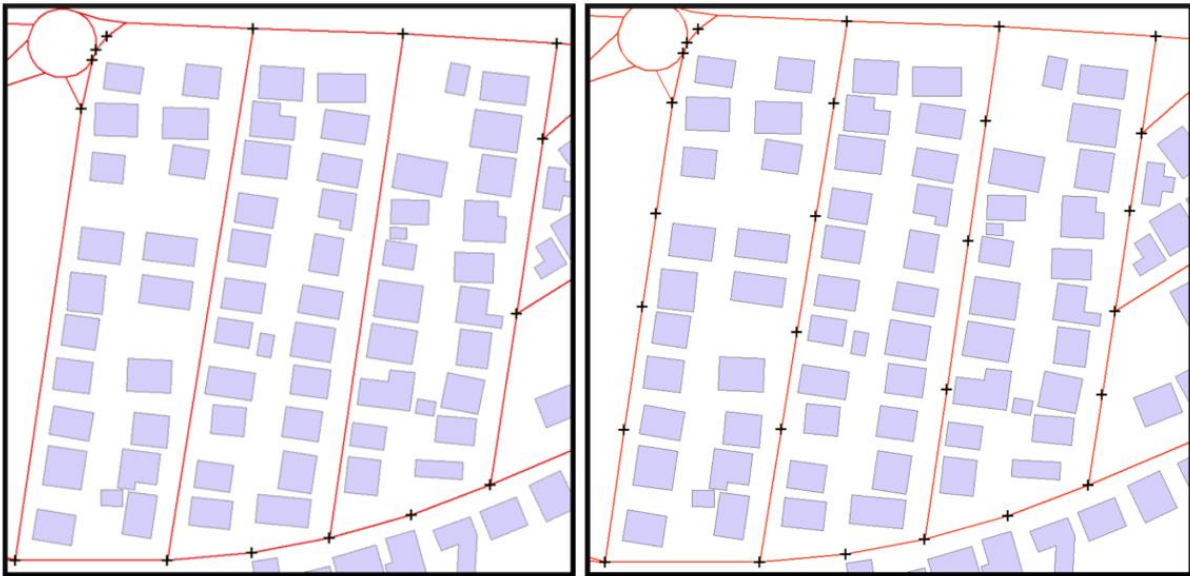


Figure 3.3: Example of editing road data by adding vertices on straight segments.

As will also be explained in the Methodology chapter, agents start their movement in the model at buildings, which represent their homes. Unfortunately, the attributes of the OSM data is not sufficient for distinguishing residential (dwellings) from non-residential buildings. To exclude non-residential buildings, a selection based on the size (area) of the buildings was performed and only those larger than 20m² and smaller than 300m² were kept as potential dwellings (see figure 3.4). The selection of this values is partially arbitrary, as no more information are available. However, it is still expected to deliver a more realistic representation of residential buildings.

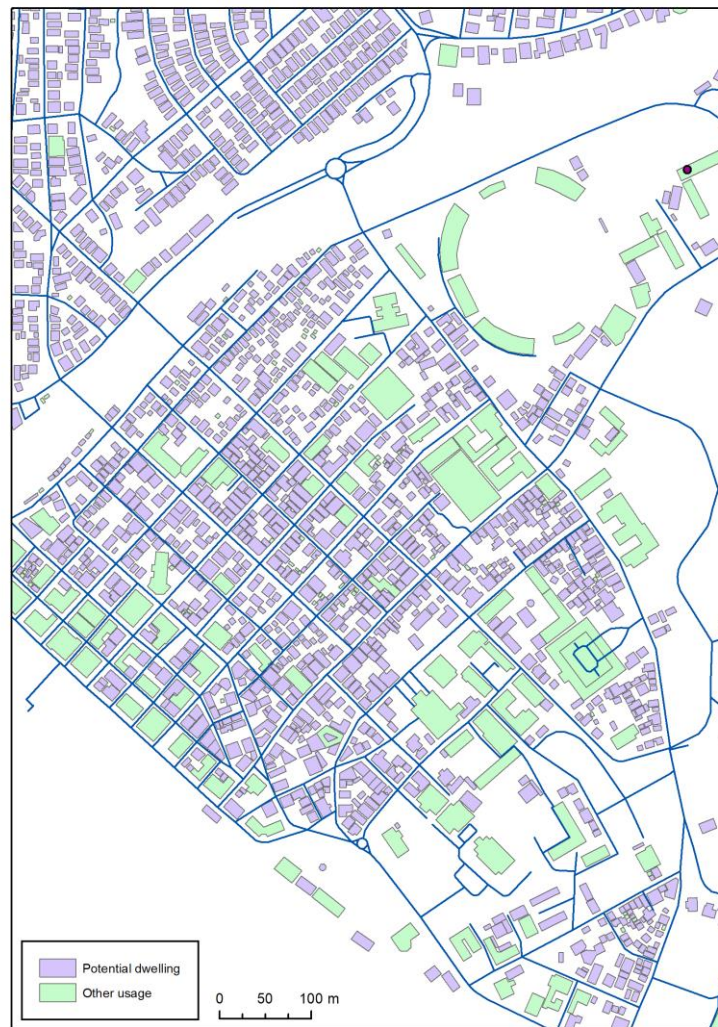


Figure 3.4: Selection of potential dwellings by building size.

The data about locations of hurricane shelters in Dominica was downloaded from the GeoNode data sharing platform of the Caribbean Handbook on Risk Information Management (CHARIM) project (Jetten et al. 2014). Nine shelters are defined in the respective study area of the city Roseau and surroundings (see figure 3.5).

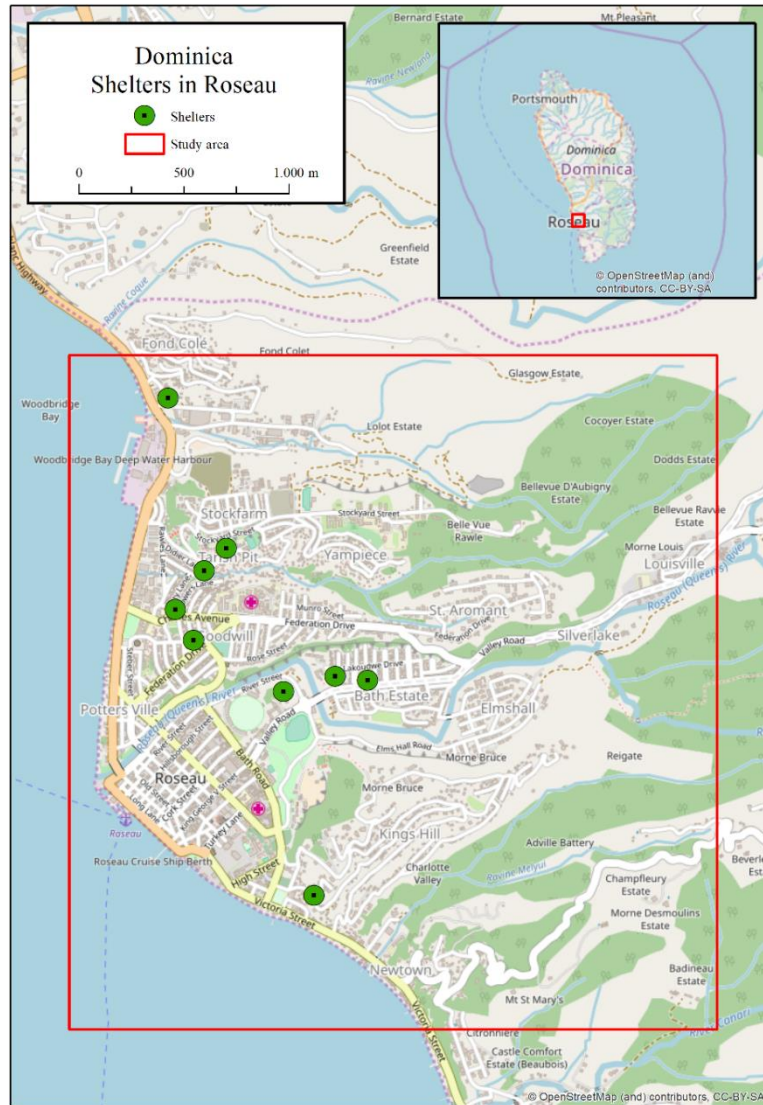


Figure 3.5: Location of shelters in the study area.

Road damage risk zones have been created based on flood-risk and landslide susceptibility, classified within the CHARIM project. Combining both raster datasets of flood risk and landslide susceptibility and reclassifying the combinations, three classes of potential risk zones were defined (see table 3.1). A classification value of 1 means a relatively low chance of a road being damaged, a value of 3 a high chance. The resulting raster data was saved in ASCII format, which is a supported file format in NetLogo. In the model, the raster data will later be used to estimate the probability of a road damage occurring during a hurricane event.

Table 3.1: Definition of risk zones based on landslide susceptibility and flood risk data.

Risk zone definition		Flood hazard extent				
		none	1:5 year rainfall	1:10 year rainfall	1:20 year rainfall	1:50 year rainfall
Landslide susceptibility	low	0	1	1	2	3
	medium	1	2	2	2	3
	high	3	3	3	3	3

As projection for the data, the UTM 20 N (EPSG:32620) was used, being a suitable projection for the area and minimizing deviation based on projection, allowing relatively precise usage of distance measurements. Additionally, transverse Mercator coordinate systems, such as the UTM system are supported by the NetLogo software.

4. METHODOLOGY

In this chapter the methodology applied in this study will be described. First, the overall idea and the following design as a conceptual model will be outlined and put into context of a reduced version of the ODD (overview, design, details) protocol. Next, the implementation of the conceptual model into NetLogo will be explained. The methodology of visualization in NetLogo will conclude this chapter.

4.1. Method Introduction

As mentioned in chapter 2, different technological concepts are feasible within the field of agent-based modeling. A spatial evacuation model can be raster-based, network-based or based on learning algorithms. The focus of this study is the movement of evacuees and their route selection for finding a way to the closest shelter. Also, damages done to road segments shall be a subject. Therefore, using a network-based approach was chosen, as it allows a focus on routing and manipulation of the network. Another advantage of using this approach is the integrated network extension in NetLogo, which offers routing algorithms based on a street network.

4.2. Model Description

For the description of the conceptual model, a standard protocol for describing agent-based models can be used. The ODD (Overview, Design, Details) protocol aims to provide a standard for describing an ABM in a way to make it easy to understand but still complete (Grimm et al. 2010). For the model of this study, an abbreviated and simplified way of the ODD protocol will be used, focusing on the overview elements. Being a prototype, not all advanced points of the protocol can be answered in a detailed way. However, it is still beneficial to stay close to the ODD's elements, allowing replication and an easy way to follow the model's inner logic.

Elements of the ODD protocol	
Overview	1. Purpose
	2. Entities, state variables, and scales
	3. Process overview and scheduling
Design concepts	4. Design concepts
	• Basic principles
	• Emergence
	• Adaptation
	• Objectives
	• Learning
	• Prediction
	• Sensing
	• Interaction
	• Stochasticity
	• Collectives
	• Observation
Details	5. Initialization
	6. Input data
	7. Submodels

Figure 4.1: The ODD protocol (Grimm et al. 2010)

The Overview part of the protocol is divided into three elements: 1) Purpose, 2) Entities, state variables, and scales, 3) Process overview and scheduling (see figure 4.1).

Purpose

The Purpose element is defined as a “clear and concise statement of the question or problem addressed by the model” (Railsback and Grimm 2012, p. 37). The purpose is elaborated by the objective of the study: Creation of a model that integrates both, infrastructure disturbances and people’s behavior in an evacuation event. More precisely, it is intended to model movement of evacuees during different phases of a hurricane event and to integrate road damages done by the first event for a following event, influencing and potentially altering the movement and shelter allocation.

Entities, state variables, and scales

Entities are the elements represented within the model. Mainly these are one or more types of agents, and a number of environments. Entities are characterized by their variables, describing their properties or attributes. Often a behavioral strategy is included. Besides the distinction of agents and environment, elements can be either dynamic or static. They can change their position or may change their (dynamic) variables during a model’s run. An environment is a surrounding in which the agents live and interact with (Railsback and Grimm 2012). Most simulation models have a number of different environments. In NetLogo, the environments are often described by patches, which correspond in a spatial explicit environment to raster layers in a GIS. Patches can have their own property, differing from one to another. However, the environment can also have global attributes, which are the same over the entire area. The

entities constituting this model are: evacuees (as agents), and the following environments: roads, buildings, shelters and “risk zones”. They will be introduced, and their variables and behavior will be described in the following section. Additionally, simplifications and assumptions of the model’s prototype shall be outlined.

The most important element of the model are the evacuees, whose movement is to be simulated. The evacuees are aggregated to households, each agent in the model representing one household. Each household is assigned a building, based on the GIS data for potential dwellings, as a home and starting point, as well as a designated point for returning after the hurricane event. Households are aware of the optimal route from their starting location to all shelters and vice versa, and know which shelter is the closest, based on the distance of the routes. By setting up the model and creating the household agents, they will directly calculate the route, as will be explained in the implementation paragraph. Once the evacuation starts, all households start their movement at the same point of time without hesitation and without decision making of whether or when to evacuate. They move at a constant speed of 1.4 meter per second. This value is a rough measure of an average preferred walking speed (Mohler et al. 2007). By picking a movement speed based on walking, a pedestrian evacuation is simulated. Furthermore, the movement is limited to roads only, the agents move on the street network. The household agents do not influence each other and do not hinder each other’s movements.

In addition to the assigned home building, each household is assigned a node of the street network, which is the closest to the home building and represents the home node. It is thereby the defined starting point on the street network for each agent. This home node serves as a base for calculation of the optimal route to the shelter. The exact potential destinations are defined by the closest nodes to each shelter. Comparing the distances, which are defined as a sum of all road segment distances on the route, the household agents picks the route with the lowest distance value for the destination of its movement. If the road network changes, which may occur during the hurricane event phases, the households will adapt their route choice accordingly, if their optimal route is affected or a different shelter is closer due to the changes in the network (see figure 4.2).

The households can have different states during the model run. They can be moving to shelter, be in a shelter, moving home, be at home or be stuck at their position. The last-mentioned state may occur if no way to any shelter or no way back home from the shelter can be found. The number of household agents in the model should reflect the population of the study area. Five thousand households is a realistic number, considering the population of Roseau (14.725). This is supported by the number of potential dwellings in the study area (5030). However, the number of households created for a simulation run be changed by the user. Based on the given description, the household agents have a number of properties, which will be defined as variables in the model implementation chapter.

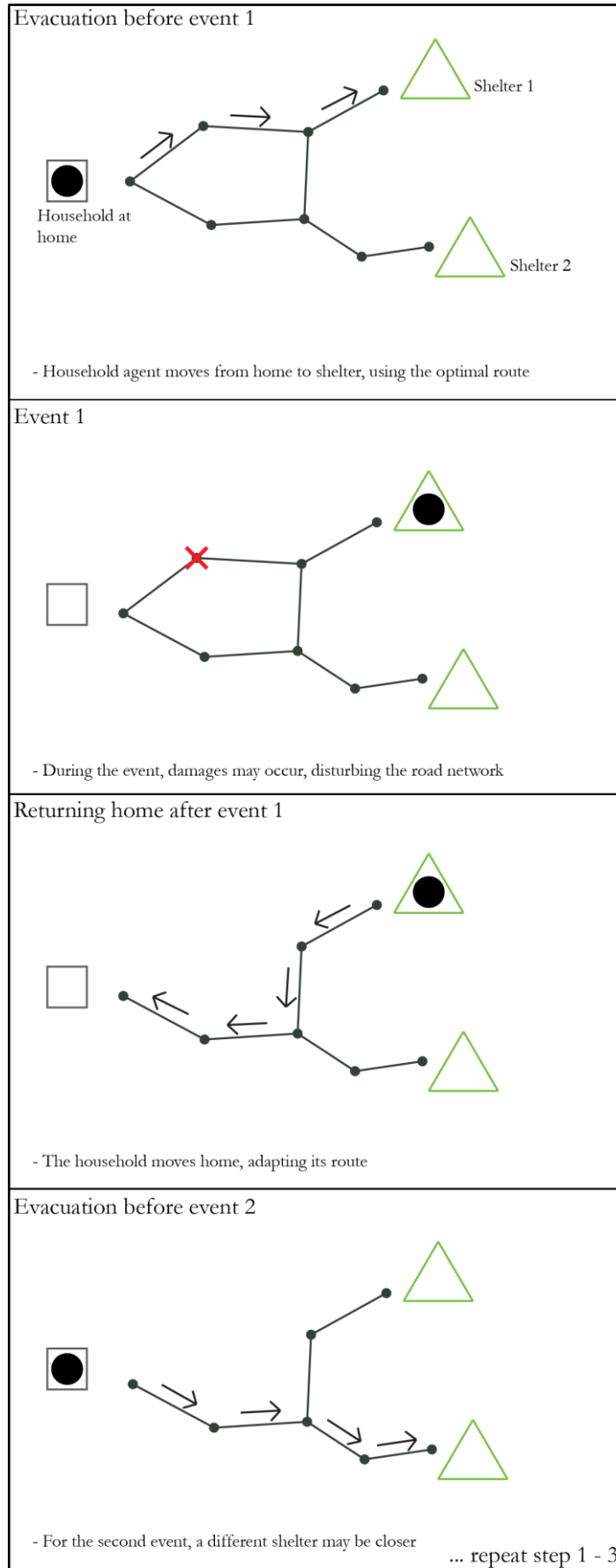


Figure 4.2: Simplified visualization of the routing, movement and shelter allocation concept of the model.

Another crucial element for the model is the road network, based on GIS data. In this model environment, the road network is formed by connected nodes, the connection being created by links. Each node describes a vertex of the road network, each link between the nodes describes an edge. The links between nodes have a weight value, which is the distance between the corresponding nodes. The nodes of the road network do not have any attributes, besides the default ones given by the software. During a hurricane event they may die, indicating a damaged road segment. If a node dies, the links to which it was connected, die as well and thereby change the road network. The probability of a node to die is based on the risk zones, which will be described later, and more precisely in which risk zone the node is located. The values for the probability are based on the study of Jetten et al. (2014). Between the two hurricane events, nodes cannot be restored, meaning conceptually that destroyed roads are not reconstructed between both disasters.

The shelter entities describe the location of shelters in the study area. They are static elements but hold dynamic variables: 1) counter for the number of people in the shelter, 2) capturing and storing the total number of people in the shelter at the first event, 3) capturing and storing the total number of people at the second event. Also, the closest node from the road network is stored as a variable, serving for the calculation of the routing and the destination of the household agents.

The last entity of the model are the patches, the spatial explicit background of the model, which is a static environment element. The most important attribute, beside the space itself is the risk zone value, which is a combination of landslide susceptibility and flood risk, as described in the data description chapter. It is a static variable, used to define the probability of a road node to die during a hurricane event, which is interpreted as road damage or road failure. The risk zone classes are loaded via the GIS extension, described later, and broken into patches, the equivalent of a pixel unit of a raster in NetLogo. Each patch has a number of attributes, defined as variables in the implementation: the static risk zone class, which is used for damage probability, two counter variables for counting the number of households per patch at each tick, one for each evacuation phase, two shelter counter variables for counting households per patch on patches where shelters are located, and a road damage variable used for storing the information where road damage occurred.

It has to be noted, that the former mentioned home nodes and shelter nodes may be affected in the phase that indicates the hurricane event, as well. In case that a node defined as home or shelter node is located on a patch with a risk of landslide or flood occurring, it may cause a node to die. This has to be interpreted the following way: if a home node dies, the house was destroyed, and the household will not return. If a shelter node dies, the shelter and the road connecting the shelter to the network was affected in a way, that it cannot be accessed (nor be left) anymore.

Besides the entities and their attributes, the temporal and spatial scale of the model need to be explained. The temporal resolution, or time step size, as one part of the temporal scale describes how one tick (time step in NetLogo) is defined. In the concept of this model two different approaches are used, depending on the phase of the simulation. During movement phases (i.e. evacuation of population, and return of population to their homes) each time step in NetLogo is one second. Using this resolution, the movement of the household agents can be modeled and observed in detail and the movement speed, defined as walking speed, is represented purposefully. However, the other phases of the model (i.e. during the hurricane event, while the population is located in the shelters, and the time between hurricane events, while the population is at home) is to be understood as an abstract time measurement. The exact period of time is not included in the model's concept. Therefore, the exact temporal extent of one model run cannot be specified as a concrete period of time precisely either. However, the model concept is designated to simulate two events in one hurricane season, with relatively short time between both events.

For the spatial scale, the total size of the study area (spatial extent) and the size of one patch (spatial resolution) must be specified. The study area extent has been predefined in GIS software. The model in NetLogo software uses the same extent. It extends around three times three kilometers (9 km²), with minor deviation. In NetLogo, the model was set up in 150 times 155 patches, giving each patch a size of around 20 times 20 meters.

Process overview and scheduling

The schedule of the model is divided into a number of phases, which contain and trigger certain procedures (see table 4.1), which will be described in more detail in the implementation part of this chapter. In general, the model consists of three phases per event. The phases are repeated for the second event under different circumstances (i.e. road network affected by damages). The phases are as follows: 1) Evacuation phase: population moving to shelters, 2) Event phase: hurricane taking place, population in shelters, damages are occurring, 3) Post-event phase, population returning home. Additionally, one phase between both phase blocks represents the time between two events, meaning that the population is at home, after the first event.

Table 4.1: Conceptual model phases.

Model phase	Concept
0	Evacuation phase. Population moving to shelters
1	Event phase. Population in shelters. Hurricane active, damages to roads.
2	Post event phase. Population returning home.
3	Phase between events. Population at home.
4 to 6	Repetition of 1 to 3.
7	Phase after second event. Population at home.

4.3. Model Implementation

The described conceptual model was implemented in code in the NetLogo software. Its' most important mechanisms and procedures will be described in this section. A focus will be laid on the classical NetLogo procedures `setup`, `create-agents` and `go`, and the procedure for optimal route calculation. The full code is attached to this thesis as a reference. For this model, the GIS, network and bitmap extensions were used, and their purpose will be revealed in the following text.

The first crucial procedure is the **setup procedure**. It is a typical first procedure for models in NetLogo and is used for loading data, initializing and preparing the model environment, and setting global variables. The setup procedure of the model for this study first loads the geodata, described in the Data Description chapter (see chapter 3.2), using the GIS extension. The geodata is then available as global variables of the model and can be used in other procedures or for visualization purposes. Using a reporter function (**shelter-locations**), the coordinates of the shelters in the study area are extracted and set to a global list variable. Additionally, counters, which will later be used for scheduling, are established and set to zero and a model phase monitor is set to a pre-model stage value. The envelope of the model is set to the spatial extent of the study area. The risk zone raster data, which is a product of landslide susceptibility and flood risk data, is applied to the patches of the model. During the setup procedures three other procedures are called. The **setup-path-graph procedure** uses the loaded geodata of the road network to create node agents at the vertices of the road data. It also creates links between nodes that are connected in the network, based on the vertices in the data. The reporter procedures **polylines-of** and **new-node-at** are necessary to do this and make use of the GIS extension to read the features of the geodata. The road network is now fully loaded in NetLogo and exists as node and link (roads) agents. This will allow the network extension to be used for further functionalities later. The **weighted-distance procedure** is a simple procedure that adds a weight variable to the roads. This weight is based on the length of the link and therefore describes the distance between two nodes, connected by a road. By calling the **setup-shelters procedures**, the shelter environment is created at the locations, defined earlier from the geodata as global variable (coordinates of the shelters). Additionally, the node from the road network which is the closest to each shelter's location is set as a variable of each shelter. Other parts of the setup are used for visualization purposes, which will be explained later.

Another classical procedure for a NetLogo model is the **create-agents procedure**. In this model it is used to create the household agents, which are the only moving agents in the concept. First of all, a random dwelling from the geodata is defined as their home location and its' coordinates are set as the agents starting location. For route calculation and movement on the road network, the household agent needs to be located on the network. Therefore, the closest node to the agent's starting location is set as the home node, which can then be used for further calculation. Also, the household directly moves to the location of the home

node. From the home node, the distance to each shelter node is calculated using the network extension, based on the optimal route and the weight value of the links (length of roads between nodes). The network extension is able to find the best route using the Dijkstra algorithm, comparing different options on the network and choosing the one with the least sum of weight (distance) values. The distances to all shelters are compared and the shelter node of the shelter with the least distance is defined as the destination for the household agent. Using the network extension again, the path from the home node to the destination node is now stored as an ordered list variable of the household agent, containing all links (edges). Also, all nodes along the route are stored as an ordered list. The list of nodes will be used for the movement, following node by node on the path. For the start of the model, the agent state variable is set to 0.

The **go** procedure is used to start the run of the model, starting the ticks and thereby the dynamic elements in the model. For the go procedure it is important to understand the model phase and agent states concepts and their interplay. In the first phase (model-phase = 0) the household agents are asked to move, based on the rules defined in the move procedure, which will be introduced later. As soon as a household arrives at its' destination, the agent-state variable is set to 1, meaning that they have arrived at a shelter. If all households have arrived at a shelter, the model phase switches to 1. At this point, a tick counter starts (after-evac-counter) and initiates different functionalities. First, the **count-shelter-1 procedure** is called, counting the households per shelter. Later, the **damage-to-nodes** procedures starts, making road nodes die with a probability based on the risk zones they are located in. The damage-to-nodes procedure uses the patches own variable of risk-zone-class for a probability for a node to die if it is located on the patch. On a patch with the highest value of the risk class (3) there is a risk of 10 percent for a node to die, 3 percent on a patch with a risk class of 2, and 1 percent on a patch with a risk class of 1. The values are an approximation based on the work of Jetten et al. (2014) in the CHARIM project. Afterwards, the **calculate-path-home procedure** calculates the best way home. This does not necessarily have to be inverse of the way the household has taken to the shelter, as the road network may have changed due to the damage-to-nodes procedure. Then, the next model-phase (2) is started, making the households return to their homes, based on the path calculated before, using the move-back procedure. While the households move, their agent-state is set to the value 2, as soon as the arrive at their home, it will be set to 3. If all have arrived at home, the next model phase (3) is set. In model phase 3, indicating the time between the two events, the calculate-path procedure is called, which repeats the calculation of the optimal path to the closest shelter, as it has been explained for the create-agents procedure. It does however, include the changed road network (due to damages) in its' calculation and thereby might change the path. The next phases (4 to 6) repeat the phase 0 to 2 with the new conditions and in the end set the model phase to 7, which indicates that the model run has finished.

Table 4.2: Implementation of model phases and the procedures called per phase.

Model phase	Procedures	Description
before	setup	Loading data and setting up environment.
before	create-agents	Creation of household agents, including first path calculation for path from home to shelter.
0	move	Household agents moving to shelters.
1	count-shelter-1, damage-to-nodes, calculate-path-home	Counting number of households per shelter. Causing damage to road network, road nodes die based on risk zone patches. Path home is calculated.
2	move-back	Household agents moving back home.
3	calculate-path	Household agents calculate path from home to shelter, based on disturbed road network.
4	move	Household agents moving to shelters.
5	count-shelter-2, damage-to-nodes, calculate-path-home	Counting number of households per shelter. Causing damage to road network, road nodes die based on risk zone patches. Path home is calculated.
6	move-back	Household agents moving back home.
7	-	Simulation run finished.

During the go procedure, the **move and move-back procedures** are called, defining the movement of the household agents. They work the same way, with the difference, that the former uses the path from the home node to the destination node, whereas the latter uses the path from the destination back to the home node. The principle of movement is, that the household moves to the first item in the ordered list of nodes it needs to follow to move on the defined path. At each tick, it reduces the distance of its' current location to the next node by the defined speed. As soon as the distance is less than the walking speed (< 1.4 meter) it directly moves to the targeted node and then removes the node from the list of nodes it needs to visit. At the following tick, the household will then move to the next node, now being the first element in the list and repeat this procedure until it reaches its' destination and the list of nodes to visit is empty. Once the household reached the destination, the agent-state is set to 1 (for the move procedure) or 3 (move-back procedure).

4.4. Model Interface and Visualizations

Another topic which was examined in this study is the model's interface and visualization of geospatial elements in the NetLogo view. First of all, it needs to be mentioned, that the overall software interface NetLogo software is static. In itself, NetLogo contains a number of dynamic interface elements. However, the composition of interface elements does not adapt to different resolutions and screen sizes. In this study, a 16:9 monitor was used, with a 1920x1080 resolution.

Considerations for the design of the interface need to be done according to users' needs. It was therefore tried to organize interface elements in a way, that makes it easy and straight-forward to use and minimizes ambiguities. For interactive elements, the user should always know what effects of his or her actions are, for example by clicking on a button element. Everything in the interface should have a clear purpose. If the user's action is required, he or she should be clearly guided through what to do and the guidance should be clearly communicated. NetLogo offers a predefined set of different interface elements. They can be grouped to interactive elements, for which user action is required or possible, and monitors and plots for additional information. The model view, dynamically displaying what is happening in the model is another element.

For the visualization of elements in the view (which is NetLogo's map body), some design considerations were included. All entities in the map should be clearly distinguishable and easy to read. During the model run, elements that change over time (household agents) should be easy to follow, as well, as other changes in time should be perceptible. After the simulation run, a visualization should assure that changes in the pattern of movement can be perceived easily. Additional information in the interface, such as line graphs and monitors were added to deliver more in-depth information, especially considering changes between both events. For this, the total number of households in shelters, the number of households per shelter and the household agents' state are measured and plotted. Monitors can display numbers text information directly and update at each tick. The number of damaged road segments, the number of stuck households and a time measurement for the evacuation are monitored in the model.

Another focus was put on the integration of cartographic elements into the view of NetLogo. Being a spatial visualization, a spatial scalebar and a legend are essential for the model view.

The resulting design and its element will be further explained in the respective result and discussed in the discussion chapter.

5. RESULTS

In this chapter the results of the former mentioned methodology will be described and supported by figures. First, the model outputs will be presented, focusing on the validation that a multi-event agent-based model, as it has been performed in this study, provides an added value and relevance in the field of disaster management. Afterwards, the interface design and its arrangement, and the model's view visualization will be explained. This must be seen in the context of a user-friendly interface, making the model easy to use, and providing a visual appealing and unambiguous visualization of geospatial and temporally dynamic content in the view. Especially the differences between both evacuations should be stressed out.

5.1. Model results and output

For model outputs, Smith et al. (2007) define a classification of three different levels for an analysis of agent-based model outputs: global, individual or event-based level. The first focuses on analysis of values and statistics, derived by the model, whereas the second looks at the changes in behavior of individual elements, such as the agent. The event-based level focuses on how an event, e.g. triggered by the environment, impacts other entities and the overall model outcome. In this study, it was examined how road damages by storm events would impact the movement of evacuees, changing their route choices and thereby shelter allocation. Also, the time for evacuation was examined, comparing the time needed for each storm event. In the sense of the classification of Smith et al. (2007), the results will be regarded, considering a combination of the individual and event-based levels.

In the methodology chapter it was explained, that each patch has a counter variable, counting the number of households located on the patch at each time step. The time steps are defined as seconds in the conceptual design of temporal resolution during the evacuation phase of the model run. These counter values lead to a pattern, which can be interpreted as a relative usage of the roads. For both events one individual counter exists and thereby allows the comparison of road usage (and route choices) in the evacuation phase. Additionally, the patches hold a road damage value, which records nodes dying on it. As the procedure of road damages, i.e. nodes dying during the event phase, includes a probability based on the predefined risk zones, the patterns of damages may be different for each simulation run. Here, one run result was intentionally chosen, revealing the influence of road damages on the evacuees' movement and shelter allocation. The combined observation of relative road usage and location of road damages allows a visual interpretation of the influences of road damages to movement patterns and shelter allocation.

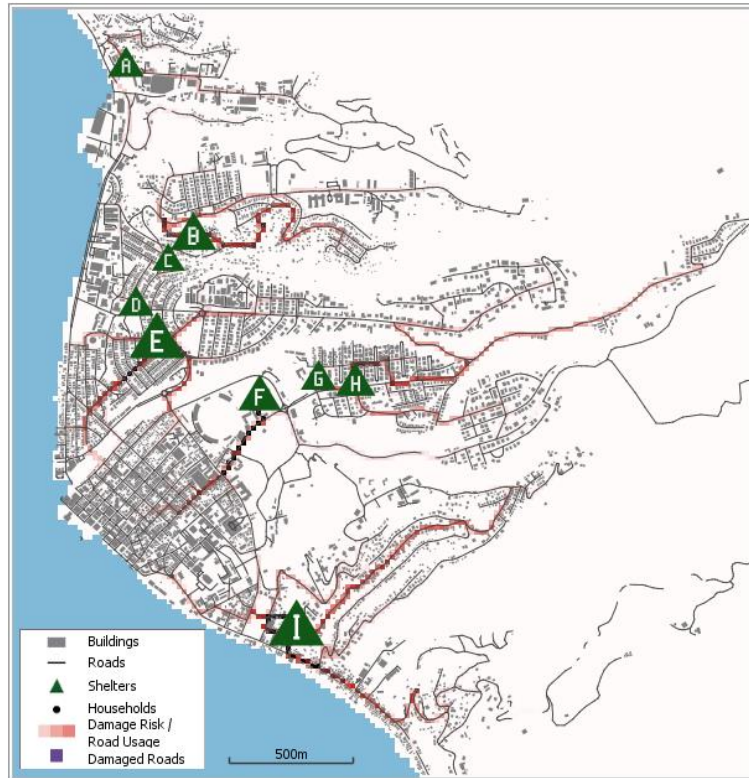


Figure 5.1: Results: Road usage and shelter allocation patterns of the evacuation for event 1.

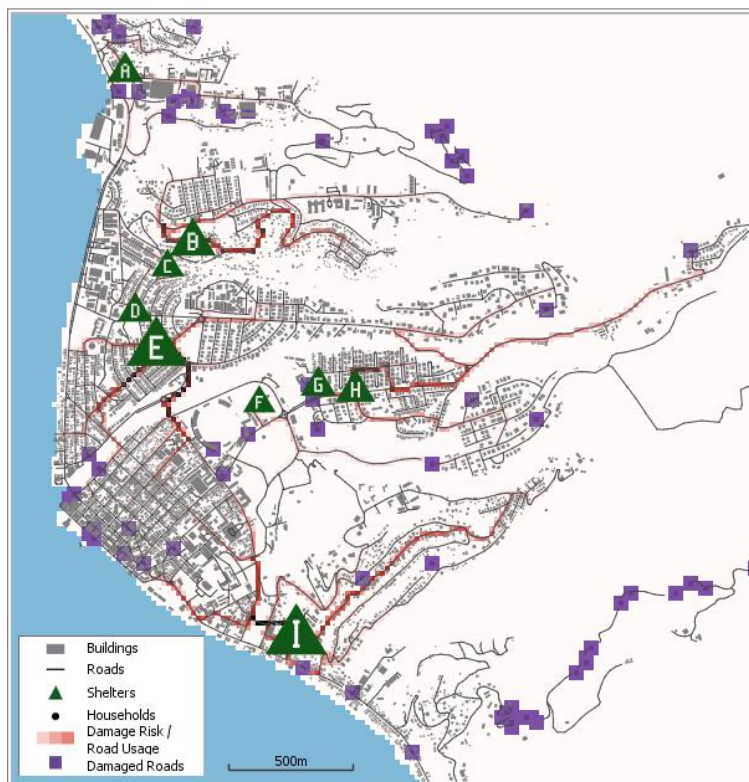


Figure 5.2: Results: Road usage and shelter allocation patterns of the evacuation for event 2, including road damages.

Looking at the figures 5.1 and 5.2, and comparing the patterns of movement for both evacuation phases, it can be observed that changes are mainly occurring in the south-western part of the study area. This can be interpreted as an effect of the combination of high number of households, existence of risk for road damage and multiple shelters in the area. The interplay of shelter allocation to shelter E, F, and I is of main interest for the interpretation of the results. At the event 1 evacuation, it can be observed that there is a high road usage on one specific route, leading out of the area of interest towards the north-east to shelter F. The road usage of event 2 however, shows a different pattern. On that precise route a road damage occurred, making the road inaccessible. Additionally, alternative routes around shelter F were damaged. This led to an increase of road usage from the respective area on a route north towards shelter E, and south towards shelter I. This should be reflected in the shelter allocations, which will be described later. Another interesting aspect is the movement from the eastern outskirt settlement towards shelter H. A road damage occurred here, making movement between the settlement and the shelter impossible, leaving a high number of households in need to stay at the shelter, as will be seen in the shelter allocation numbers later. The road usage towards shelter H is therefore reduced significantly at the second evacuation.

Another interesting measure to be observed is the number of households per shelter for each event (see table 5.1). Due to the road damage issues explained before, the percentage of households seeking shelter in shelter F reduced substantially. At the same time the values for households in shelter E and I increased. It can be further observed that shelter H holds a large number of stuck households, not being able to return to their homes. This has to be seen with connection to the cut-off outskirt eastern settlement, described earlier.

Table 5.1: Households per shelter for both events.

Shelter	Event 1	Event 1 Percentage	Event 2	Event 2 Percentage	Tendency	Stuck in shelter
A	300	6	300	6	=	20
B	709	14,18	709	14,18	=	12
C	105	2,1	105	2,1	=	6
D	221	4,42	221	4,42	=	0
E	1146	22,92	1361	27,22	↑	60
F	595	11,9	85	1,7	↓	11
G	264	5,28	264	5,28	=	22
H	374	7,48	374	7,48	=	113
I	1203	24,06	1498	29,96	↑	34
Stuck home	83	1,66	83	1,66		

The time needed for evacuation is a calculated product of the distance from a household's home to a shelter, based on the calculated optimal route, and the walking speed of 1.4 meter per second. The mean time of the households needed to get to a shelter is 14:54 minutes (14.9) for event 1 and 14:20 minutes (14.34) for event 2. The maximum time for event 1 is 65:50 minutes (65.83) for event 1 and 51:24 minutes (51.4) for event 2. An increase of time has been expected but the opposite occurred. This again has to be seen in connection with shelter H and the outskirt settlement, mentioned before. The households moving from this settlement to shelter H have a long distance to cover and therefore need much time to reach the shelter. As they were not able to move back after event 1, the high values of time they would need to travel do not influence the aggregated value of event 2 anymore. The statistical and interpretative value of the evacuation time therefore has to be regarded with caution, as the effect of statistical outliers has been underestimated. Recommendations for an improved statistical analysis are given in the discussion chapter.

5.2. Visualization in NetLogo

For the interface design of the model in NetLogo, it was tried to fulfil basic principles for interface design and follow standards and convention of NetLogo models, allowing the creation of an easy to use application. To achieve this, the interface elements were divided and arranged in three groups: interactive elements that require user action, model view, and additional information (monitors, plots, etc.) (see figure 5.3). These were arranged in a logical order from left to right. For the elements requiring the user's action, guiding texts were included, informing the user at each stage where his or her action is required. Also, the elements were ordered from top to bottom, starting with the first action required at the top left side. In the middle of the interface arrangement, the model view can be found. This way, it draws most attention to it and its position allows the concurrent usage of the interactive elements on the left and observation of additional information, which were placed on the right side of the interface arrangement. All elements were snapped to the grid, a function of NetLogo to assure that elements are placed and arranged at the same horizontal or vertical position in the interface.

Three plots were included, one being a histogram, two being line plots. They are updated at each tick of a model run. The histogram plot displays bars for the household states, as explained in the methodology. The stuck households are not included in the bar plot but indicated in an extra monitor on the right side of the histogram. The two line plots show the number of household agents in shelters, one displaying the total number of households, the other households per shelters. Colored lines in the second line plot indicate the corresponding shelter for each line. Additional value and counter displays hold information about the number of damaged road segments, the mean time for households from home to shelters for each event and the meters per patch value. This value stays constant during the model run but might change if the model settings are altered. It can also be interpreted as a spatial resolution indicator, informing the user of

the size of one patch. In addition to this, the model phase monitor informs the user about the phase the model is currently running and displays an information, once the model has finished.

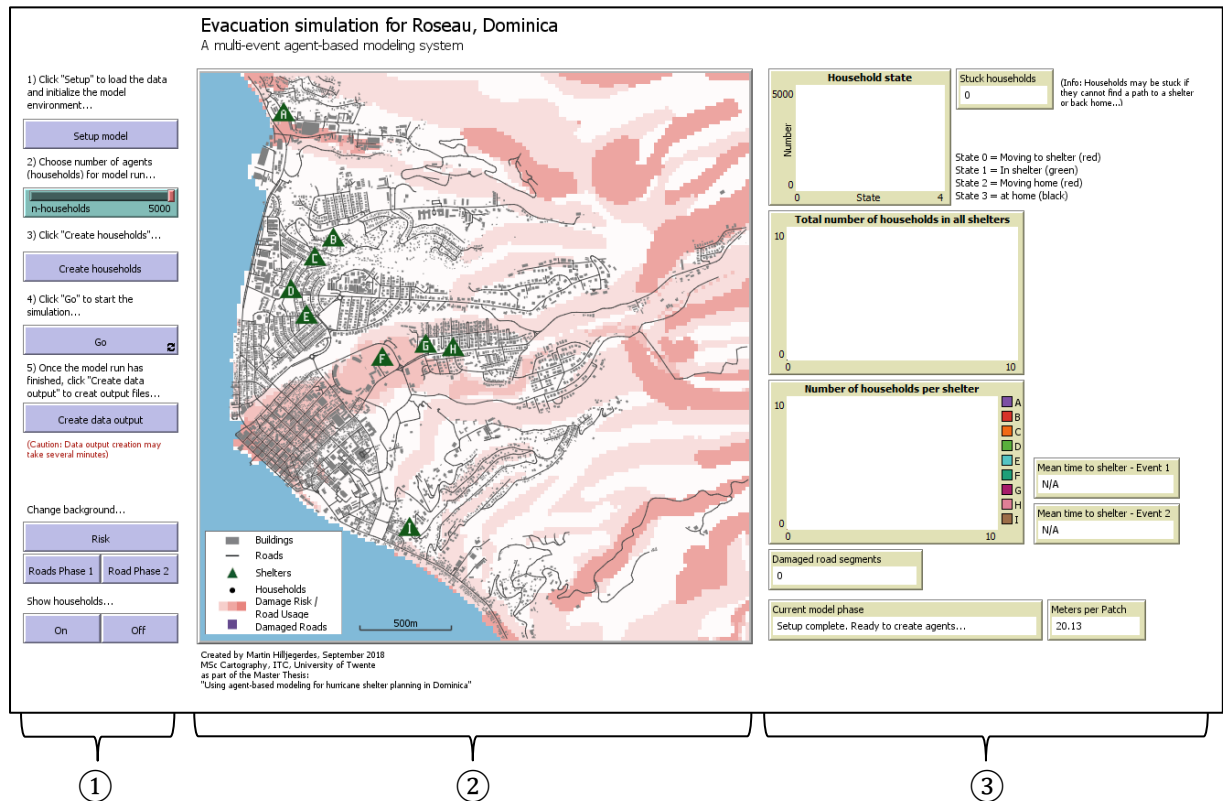







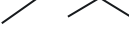



Figure 5.3: Screenshot of the interface arrangement. 1: Interactive and elements requiring user action. 2: Model view. 3: Additional dynamic information (Plots and monitors).

For the visualization in the model view, the main target was to provide clearly distinguishable elements, and a visual appealing color scheme. As the extent is static and set by NetLogo and no navigation is possible within the view, simple symbols needed to be used, to not overload the perception and cognition of the user. Especially if the maximum number of household agents is to be modelled, any details in symbolization may become disturbing. For the household agents, which represent the entity with the highest number and are the only moving element in the view, a filled circle was chosen. During the model run, the household agents will change their state several times, from being at home, moving to shelter, being in shelter and returning home. These states are represented by a changing color (see table 5.2). The shelters are represented by a green triangle, containing a number making a reference to the line plot, plotting the households per shelter. Even though the shelters are a static entity and do not move, they hold a dynamic variable which is used for visualization. The size of the triangle symbol changes and adapts at each time step, depending on the number of households it is housing.

Other static entities, such as buildings and roads are regarded as background and therefore symbolized by an unobtrusive grey. A differentiation between roads and buildings is possible by using a darker grey for the roads, and a lighter one for the buildings. Roads segments may disappear when they are damaged during the hurricane. The location of the road damage is marked by a purple square at the background. For the risk zones background information, a light red color scale is used. During the model run and after completion, the user has the option to switch to the road usage background information, using a similar color scheme. The interface option to change between different patch values (risk zones, road usage in first evacuation and road usage in second evacuation) allows the user to switch between these visualizations and compare, most interestingly, the road usage differences between the evacuations.

Table 5.2 provides an overview of the visualizations used in the model view of this study.

Table 5.2: Visualization of entities and their dynamics in the model view.

Entity	Symbol	Dynamic visualization	Description
Household			Changing color based on agent state
Shelter			Changing size based on number of people in shelter
Road			Removal of segments based on damage
Building		-	-
Risk zone / road usage		-	User can change visualization of patches, to compare the road usage of both evacuations.
Road damage location		-	Occurring on patches where damage occurred

Some additional cartographic content was added to the view, as they are necessary for a spatial visualization. By using Adobe Illustrator software, a simple legend was created as an image, displaying the meaning of each symbolization. The image was loaded into NetLogo and placed in the view using the bitmap extension. As an image, the legend is static and will not adapt to dynamic changes which may occur during a model run. For the scalebar, a line was measured and drawn in GIS software and then loaded into NetLogo and drawn similarly as in the case of the buildings. Finally, a title was added in the interface above and author and additional information were added as text element underneath the view.

6. DISCUSSION

In this chapter the results described in the last one will be discussed and put into context of potential usage in disaster management. First, ideas will be given about how results of a model, as set up in this study, can be used to improve disaster preparedness. Then, the simplifications and assumptions made in the conceptual model are discussed and suggestions are made, how the value of the model results can be improved by reducing these simplifications and adding more functionalities to the model. Subsequently, the interface and visualization of the model results and its' limitations are made subject of discussion.

6.1. Potential usage of model results

Once the model is set up and the output is created, it still needs to be discussed what can be done with the information on a substantial level. More precisely: what is the added value and benefit of using a multi-event model, as it has been done in this study, instead of a single event model? As it has been defined in the introduction chapter, there is a need of increasing the preparedness for disaster events. In this context, the discussion can be about how planning authorities, responsible for disaster management, or other involved decision makers can use the results for this purpose.

The changed road usage and route choices for a second event evacuation, depending on the damages occurring during the first event, may deliver valuable information about critical road segments and sections. If a shelter is connected to a highly populated area by a limited number of roads only, and if these roads are in risk of being disturbed, the movement pattern of the evacuation may change dramatically. This was observed clearly in the exemplary model run, described in the results chapter of this study. Using this information, planners are enabled to define critical road segments and then decide for road fortifications, or definition up to construction of alternative routes leading to the corresponding shelter. Additionally, prioritization of road reconstruction can be done. If the time between events is limited, especially if two events might occur in the same season, it is crucial to know which roads need to be reconstructed first after the event, to provide an effective evacuation for a potential second one. In the end, the information provided by the model might lead to realization that the location of a specific shelter is unsuitable, as the risk of it being inaccessible is very high. Therefore, a multi-event evacuation model can be used for evaluation of location and accessibility of shelters.

Furthermore, the results of the model run revealed, that a disturbed road network can lead to changes in the numbers of people (or households) per shelter. The model results and the derived information can be used for evaluation of shelter allocations. One effect may be, that if one shelter is not accessible for a second

event evacuation, that other shelters in the area are used by a larger number of evacuees. By using a model taking this into account, the planner can be prepared and avoid an unexpected overload of one shelter. Also, a shelter can be cut off in a way, that people cannot return home, as the roads leading back to populated places and settlements are not usable anymore. To be prepared for this, shelters which are identified as being in risk of inaccessibility after one event and therefore need to house evacuees for a longer time, may need to stock up their supplies.

In the end, a strength of each model is the possibility for the user to experiment with it. A planner might try out different what-if scenarios, intentionally removing certain road segments after the first event and evaluate the consequences. Reacting to potential consequences before they occur can be an effective way for raising disaster preparedness.

6.2. Model improvements and disucssion

In the methodology chapter the conceptual model for this study was described in detail, including simplifications and assumptions. It is in the nature of modeling that a simplified but purposeful representation of the real word system is formulated (Railsback and Grimm 2012). However, reducing simplifications and including more functionality can be a way to increase the value of the results and generate a more (statistically) realistic output. Some conceivable improvements of the conceptual model and its' implementation will be discussed in the following section.

First of all, it would be advantageous for the conceptual model to redefine and extend the ODD protocol, including additions as mentioned in this chapter. For the prototype version of the model in this study, only the overview part of the protocol was used. If the model is developed further and more complex functionalities are integrated, the protocol should be updated accordingly, including the design concepts and details part.

In the model, all household agents are the same. Of course, this is not a realistic representation of the reality. Households may differ in their composition (number of people, generations etc.) and each member of each household has his or her own properties. Including more attributes into the household agents may provide more detailed results, if modeled properly. It might also be feasible to model individuals instead of households. Perhaps not all members of a household evacuate, but some stay behind. Additionally, individual attributes, such as age or health indicators could influence the decision to evacuate or not, as well as they may influence the walking speed. To represent a more realistic population, the walking speed would need to be adapted to certain individual attributes and perhaps include a dispersion, as not all people walk with the same speed. Also, social indicators such as income, wealth or employment might play a role in a decision-making process for evacuation. To enable the implementation of these functionalities, reliable data about the population needs to be included. The spatial distribution of population attributes is very likely not

to be a uniform distribution. Therefore, spatial information would be needed, too. A possible way of implementation is the integration of a synthetic population, trying to portray a potentially realistic population. Again, the key would be information in form of data about the population, its' attributes and spatial distribution. Furthermore, the influences of properties on the decision-making and the walking speed need to be based on scientific findings. The decision-making process itself is a functionality, which would be fundamental to be integrated. In this the model of this study, all households evacuate at the same time. For a more realistic representation, the agents would need to decide whether to evacuate at all, and if so, at what time. The decision might be based on other agents. In the proposed model, there is no direct interaction between agents. In reality and in a more realistic model, households or individuals communicate with each other, potentially leading to the decision to evacuate. In the model of this study the assumption was made that the household agents know the best route to the closest shelter at each stage of the model. This might not be the case. They may decide to evacuate to a different shelter or take a different based on personal preferences or they are influenced by other agents, for example family members or friends, evacuating to a shelter which is further away. Additionally, evacuees perhaps make irrational decisions, especially in a state of panic, which can be presumed in an evacuation event. For example, they may return home halfway or spontaneously decide to alter the route or the shelter they are moving to.

Information of other entities in the model can be beneficial, as well. Knowing which buildings are residential and how many people live at each building would allow a realistic set-up, placing agents (individuals or households) at their homes for the evacuation start. However, not all people will be at their home at the start of the evacuation. Depending on the time of day and other influencing circumstances, people might be at a different location. For the roads, information about their surface (paved or unpaved) and width could be included, as these factors may influence the vulnerability towards disasters. The width could be used for a maximum number of people on a road segment per time step, also allowing the introduction of a blocked road functionality. Shelters could have a maximum capacity attribute, allowing the implementation of overcrowding. As defined conceptually, destroyed roads remain unusable for the second event evacuation. Defining a reconstruction function, allowing roads to be repaired between the events, could be a valuable addition to the model. Not all roads would be repaired at the same time and immediately, but with a certain order and time needed for reconstruction, which would be needed to be defined. The definition of the probability for road to be damaged is based on the classification of risk zones. Being a rather simple combination of flood risk and landslide susceptibility, there is room for improvement, defining a more complex and realistic road damage concept. In this context, the integration of a remote-sensing based approach could provide useful information. Analyzing images, depicting the outcome and influences of past events and performing a road damage detection might be an option to derive more realistic and generic damage rules.

For timing and scheduling, the model provided in this study uses a combination of concrete (second per tick while agents are moving) and abstract (time of event and time between events) temporal resolutions. Defining the period of time an event is taking place (hours) and the time between events (days, weeks, months) and combining these time definitions with the evacuation, leads to a complex temporal granularity issue, potentially combining different scales. However, solving this issue and integrating a more realistic scheduling systematic would lead to a more realistic representation of the real-world system. Dividing the model schedule into three segments, each with its' own temporal resolution, could be an option. Furthermore, in the scheduling of this model the hurricane “waits” until all evacuees arrive at the shelters before taking place. A different solution for defining the timing of the hurricane event would be desirable. The disaster event itself is not modeled directly in this study. Hurricanes or tropical storms can have a very different impact, depending on their path or intensity. Including a variety of different hurricane scenarios into the model would be an asset.

For a more realistic output and statistical evidence, multiple model runs following a statistical analysis and validation of the results would be needed. Also, more valuable statistical information for the evaluation of time necessary for evacuation is needed. This could, for example, take outliers and extreme values into account.

Some of the previously mentioned functionalities might require the integration of submodels from different research areas and perspectives. This could, among others, relate to hurricane models from meteorology, road and building damage and reconstruction from engineering, early warning systems and risk communication from disaster risk research, damage detection from remote-sensing and decision making in extreme situations from psychology, to name a few. In general, the cooperation with other disciplines should be strived for. On the one hand including submodels as mentioned before and on the other hand trying to use the model approach in different contexts. Finally, the model should be tested and extended to other, potentially larger study areas, further testing and recalibrating the model prototype.

6.3. Interface, visualization und usability discussion

In the course of this study, the interface design and visualization of spatial elements in the model view were examined. Some limitations of the software and possible improvements were observed and will be discussed in this section

The interface design was conducted by following general interface design standards and conventions of models in NetLogo software. However, the final usability needs to be tested and evaluated further. In general, the potential user needs to be involved in further development. User requirement studies should be performed and the usability of the interface and the application in general should be examined.

A strength of NetLogo software is the possibility of directly observing movements or other dynamics of agents in the view. This visualization, similar to an animation, enables the user to see temporal changes immediately, also giving the user control of the speed of the model. However, for geospatial information display and design considerations in the model view, the potential is limited by the static environment of NetLogo interface. The view always holds the same spatial extent and navigation, such as zooming and panning, inside the view is not possible. The only possibility of navigation is selecting an element in the view, for example a patch, and observe it in a new window. Here, navigation is possible but also rather cumbersome. With the static spatial extent of the view, the maximum extent for a study area is rather limited as well. In the context of this study, an extension of the study area would be almost impossible, without making the distinction between elements impossible.

Only simple symbolization is possible without distracting and overloading the users' perception and cognition in the view. The more dynamic elements are depicted, and the more moving agents are modeled, the more complicated a clear and easily distinguishable design concept is realizable. More dynamic and modern navigation options in the model view would be desirable. Additionally, the direct integration of cartographic elements, such as a dynamic legend and a spatial scale bar, are not feasible directly. Using an external software (e.g. GIS or graphic software) is laborious and unnecessary complex.

In this study, only the visualization within the NetLogo software itself was examined. The output data generated by a model can also be visualized in a GIS or similar software. As the results hold a spatial and a temporal component, spatio-temporal visualization options need be examined in the context of agent-based model results. If multiple runs are performed, and statistical and probability values are generated, another dimension may come into play for visualization considerations. Therefore, the visualization options for spatio-temporal stochastic model results need to be examined as well for a sophisticated use of the model's output. Regarding the output data of the model in this study, it should be further looked into the options of how to visualize and analyze the changes of movement patterns for each evacuation phase.

7. CONCLUSION

In the course of this study, a prototype agent-based model was successfully created, combining disturbances of infrastructure and the evacuation movement of the population in the case of a hurricane event on the island of Dominica. The prototype makes use of a multi-event scenario and a network-based routing systematic. It was revealed that damages to infrastructure can have a significant influence on movement patterns and route choices, leading to changes in the road usage and shelter allocations. Additional examinations were performed to create a user-friendly interface design and an elaborated visualization of geospatial content and output in the model, allowing the user to examine the changes.

It was identified that the multi-event model can be used to find critical road segments and problematic shelter locations, considering their accessibility. This might give planners an idea how to take measures to improve the preparedness for hurricanes and similar events. Being a prototype model, it was realized and discussed that the simplifications done in the model concept need to be reduced to achieve more sophisticated and realistic results. Considering the visualization aspects, a functional interface design and geospatial visualization in the model view were created. However, limitations and room for improvement were identified and discussed.

Future research and development need to be conducted for the model concept and the implemented prototype. Creating a more sophisticated and realistic model can lead to important information and insights to improve the planning of evacuation events and beyond. Furthermore, a creation of a cartography extension or integration of cartographic elements into the GIS extension for NetLogo or similar software is suggested. As the usage of geoinformation in modeling gets more and more popular (Railsback and Grimm 2012) and ever more spatial problems are to be analyzed, the visualization of spatial elements and navigation inside of modeling software and the visualization of resulting outputs need a sophisticated cartographic framework. Extensive user research, such as user requirement and usability studies, are required to support the further development of the model concept and prototype created in this study.

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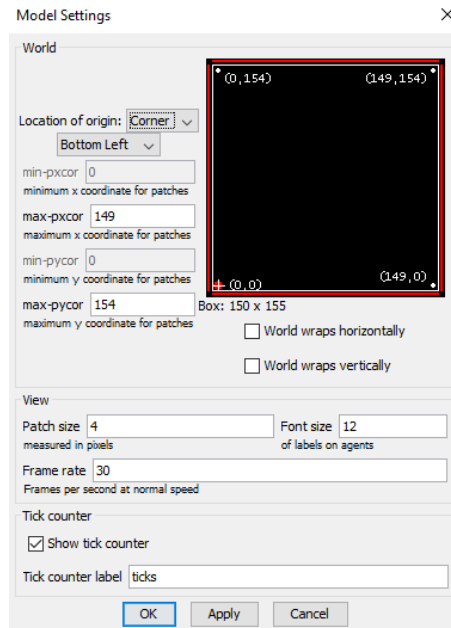
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ANNEX

a) Model settings



b) Full NetLogo code

extensions [gis nw bitmap]

globals [buildings-data residential-data roads-data shelters-data shelters-location shelter-nodes study-area-data landsl-risk-data flood-risk-data risk-zones-data after-evac-counter after-return-counter minute-counter model-phase road-usage-phase-1 road-usage-phase-2 road-usage-1-output road-usage-2-output shelter-phase-1 shelter-phase-1-out shelter-phase-2 shelter-phase-2-out damaged-roads dmg-roads-output scalebar]

patches-own [landsl-risk-class risk-zones-class counter-phase1 counter-phase2 shelter-counter-1 shelter-counter-2 road-dmg]

breed [nodes node]

breed [households household]

breed [shelters shelter]

undirected-link-breed [roads road]

roads-own [weight]

households-own [home-location destination home-node speed travel-path travel-path-home travel-path-total travel-path-home-total agent-state status-report distance-path-1 distance-path-2]

shelters-own [closest-node in-shelter-counter in-shelter-phase-1 in-shelter-phase-2]

```
; ----- Setup - Loading GIS data etc. -----  
-----
```

to setup

ca

ask patches [set pcolor white]

```
gis:load-coordinate-system ("study_area_definition.prj")  
set buildings-data gis:load-dataset "buildings_utm.shp"  
set residential-data gis:load-dataset "residential300.shp"  
set roads-data gis:load-dataset "roads_utm.shp"  
set shelters-data gis:load-dataset "shelters_utm.shp"  
set study-area-data gis:load-dataset "study_area_definition.shp"  
set scalebar gis:load-dataset "scalebar.shp"  
set landsl-risk-data gis:load-dataset "landsl_risk_utm.asc"  
set flood-risk-data gis:load-dataset "flood_risk_utm.asc"  
set risk-zones-data gis:load-dataset "risk_zones.asc"
```

set shelters-location shelter-locations

set after-evac-counter 0

set after-return-counter 0

set model-phase 999

gis:set-world-envelope-ds (gis:envelope-of study-area-data)

gis:apply-raster risk-zones-data risk-zones-class

ask patches [

ifelse risk-zones-class >= 0 [set pcolor scale-color red risk-zones-class 14 0] [set pcolor sky + 2]]

gis:set-drawing-color gray - 0.5

gis:fill buildings-data 1

gis:set-drawing-color black + 2

gis:draw scalebar 1.5

gis:set-drawing-color blue used for internal calculations, not for visualization - placements of the agents

```

;gis:draw residential-data 1
;gis:set-drawing-color green      replaced by shelter agents being visualized
;gis:draw shelters-data 3.5
;gis:set-drawing-color grey      replaced by the road network, node links being visualized
;gis:draw roads 1

```

```

setup-paths-graph
weighted-distance
setup-shelters

```

```

ask roads [
  set color grey - 2.5 ]

```

```

bitmap:copy-to-drawing (bitmap:import "legend.png") 5 500

```

```

reset-ticks

```

```

end

```

```

; ----- Agent-related -----

```

```

to create-agents

```

```

  create-households n-households

```

```

  [

```

```

    set home-location gis:location-of ( gis:centroid-of ( item random (length gis:feature-list-of residential-
data) gis:feature-list-of residential-data ))

```

```

    setxy ( item 0 home-location ) ( item 1 home-location )

```

```

    set color black

```

```

    set shape "dot"

```

```

    set size 3.5

```

```

    set speed 1.4 / meters-per-patch

```

```

    set status-report ["Waiting..."]

```

```

set home-node one-of nodes with-min [ distance myself ]
move-to home-node

; First path calculation
let agent-shelter-distances []
let shelter-dest-node []

ask home-node [
  foreach shelter-nodes [ i -> set agent-shelter-distances lput nw:weighted-distance-to i weight agent-
shelter-distances]]
  if agent-shelter-distances = [false false false false false false false false false] [ set status-report ["No way
to shelter. Staying home..."] set agent-state 9 stop]
  set distance-path-1 ((min agent-shelter-distances) * meters-per-patch)
  set shelter-dest-node (item (position (min agent-shelter-distances) agent-shelter-distances) shelter-
nodes)
  set destination shelter-dest-node

let path []
let individuals-on-path []
nw:set-context nodes roads
let dest-node destination

ask home-node [
  set path nw:weighted-path-to dest-node weight
  set individuals-on-path nw:turtles-on-weighted-path-to dest-node weight]

set travel-path individuals-on-path
set agent-state 0

if travel-path = FALSE Or travel-path = 0 [set agent-state 9 set status-report "No way to shelter.
Staying home..." stop]

set travel-path-total travel-path
]
set model-phase 998
end

```

```

to setup-shelters
  set shelter-nodes []
  foreach shelter-locations [ [xy_coords] ->
    create-shelters 1 [
      setxy (item 0 xy_coords) (item 1 xy_coords)
      set color 62
      set size 7
      show-turtle
      set closest-node one-of nodes with-min [distance myself]
      set shelter-nodes lput closest-node shelter-nodes]]
  ask shelters [
    if who = 3605 [set shape "triangle_g" ]
    if who = 3606 [set shape "triangle_h" ]
    if who = 3607 [set shape "triangle_a" ]
    if who = 3608 [set shape "triangle_c" ]
    if who = 3609 [set shape "triangle_d" ]
    if who = 3610 [set shape "triangle_i" ]
    if who = 3611 [set shape "triangle_f" ]
    if who = 3612 [set shape "triangle_e" ]
    if who = 3613 [set shape "triangle_b" ]
  ]

end

to go
;preparation

  if model-phase = 998 and all? households [agent-state = 0 or agent-state = 9] [set model-phase 0]

;model-phase 0
  if model-phase = 0 [
    ask households [move speed]]

  if model-phase = 0 and all? households [agent-state = 1 Or agent-state = 9 ] [set model-phase 1]

```

```

;model-phase 1
  if model-phase = 1 and after-evac-counter = 1 [count-shelter-1]

  if model-phase = 1 and after-evac-counter = 5 [ damage-to-nodes ask patches [ if road-dmg >= 1 [ set
pcolor 114 ask neighbors [set pcolor violet] ]]]

  if model-phase = 1 and after-evac-counter = 10 [calculate-path-home]

  if model-phase = 1 and after-evac-counter = 60 [set model-phase 2 set after-evac-counter 0]

;model-phase 2
  if model-phase = 2 [
    ask households [move-back speed]]

  if model-phase = 2 and all? households [agent-state = 3 Or agent-state = 9] [set model-phase 3]

;model-phase 3
  if model-phase = 3 and after-return-counter = 10 [calculate-path]
  if model-phase = 3 and after-return-counter = 60 [set model-phase 4 ]

;model-phase 4
  if model-phase = 4 [
    ask households [move speed]]
  if model-phase = 4 and all? households [agent-state = 1 Or agent-state = 9] [set model-phase 5]

;model-phase 5
  if model-phase = 5 and after-evac-counter = 1 [count-shelter-2]

  if model-phase = 5 and after-evac-counter = 5 [ damage-to-nodes ask patches [ if road-dmg >= 1 [ set
pcolor 114 ask neighbors [set pcolor violet] ] ]]]

  if model-phase = 5 and after-evac-counter = 10 [calculate-path-home]

  if model-phase = 5 and after-evac-counter = 60 [set model-phase 6]

```

```

;model-phase 6
if model-phase = 6 [
  ask households [move-back speed]]

if model-phase = 6 and all? households [agent-state = 3 Or agent-state = 9] [set model-phase 7]

;model-phase 7
;if model-phase = 7 [ data-output ]

if model-phase = 7 [ stop ]

if model-phase = 1 and after-evac-counter < 60 [ set after-evac-counter after-evac-counter + 1 ]
if model-phase = 3 and after-return-counter < 60 [ set after-return-counter after-return-counter + 1 ]
if model-phase = 5 and after-evac-counter < 60 [ set after-evac-counter after-evac-counter + 1 ]

;agent-state
ask households [
  if agent-state = 0 [set color 14 ]
  if agent-state = 1 [set color green]
  if agent-state = 2 [set color 14 ]
  if agent-state = 3 [set color black]
  if agent-state = 9 [set color brown ] ]

set minute-counter ticks / 60

;households per patch counter
ask households [
  if (agent-state = 0 Or agent-state = 2 ) And model-phase = 0 [ask patch-here [ count-households-1 ]]]

ask households [
  if (agent-state = 0 Or agent-state = 2 ) And model-phase = 4 [ask patch-here [ count-households-2 ]]]

```

```

;households per shelter counter
ask shelters [
  let households-counter 0
  ifelse closest-node = nobody
    [ set households-counter 0 ]
    [ ask closest-node [ ask patch-here [ set households-counter count households-here ]]]

  set in-shelter-counter households-counter
  if model-phase = 1 and after-evac-counter = 2 [set in-shelter-phase-1 in-shelter-counter]
  if model-phase = 5 and after-evac-counter = 2 [set in-shelter-phase-2 in-shelter-counter]
  let resize ( in-shelter-counter / n-households ) * 23 + 7
  set size resize]

tick

end

to move [dist]
  if travel-path = FALSE Or travel-path = 0 [ set status-report ["No way to shelter. Staying home..."] set
agent-state 9 stop ]
  if length travel-path = 0 [set color green
    set agent-state 1 set status-report ["In shelter..."] stop]
  if agent-state = 9 [ stop ]
  set agent-state 0
  face item 0 travel-path
  set status-report ["Moving to shelter..."]
  let dxnode distance item 0 travel-path
  ifelse dxnode > dist [forward dist]
  [move-to item 0 travel-path ifelse length travel-path > 0
    [set travel-path remove-item 0 travel-path][set agent-state 1 set status-report ["In shelter..."]]]
end

```



```

to move-back [dist]
  if travel-path-home = FALSE Or travel-path-home = 0 [ set status-report ["No way back. Staying in
shelter..."] set agent-state 9 stop ]
  if agent-state = 9 [ stop ]
  if length travel-path-home = 0 [set color black set agent-state 3 set status-report ["Home."] stop]
  set agent-state 2
  face item 0 travel-path-home
  set status-report ["Returning home..."]
  let dxnode distance item 0 travel-path-home
  ifelse dxnode > dist [forward dist]
  [move-to item 0 travel-path-home ifelse length travel-path-home > 0
  [set travel-path-home remove-item 0 travel-path-home][set agent-state 3 set status-report ["Home."]]]
end

```

```

; ----- Path calculation -----

```

```

; ----- Note: First path calculation is done in the create-agents procedure -----
-----

```

```

to calculate-path
  ask households [
    set home-node one-of nodes with-min [ distance myself ]
    move-to home-node
    let agent-shelter-distances []
    let shelter-dest-node []
    ask home-node [
      foreach shelter-nodes [ i -> ifelse i = nobody [set agent-shelter-distances lput FALSE agent-shelter-
distances]
        [set agent-shelter-distances lput nw:weighted-distance-to i weight agent-shelter-distances]]]
    if agent-shelter-distances = [false false false false false false false false] [set color red set status-
report ["No way to shelter. Staying home..."] set agent-state 9 stop]
    set distance-path-2 ((min agent-shelter-distances) * meters-per-patch)
    set shelter-dest-node (item (position (min agent-shelter-distances) agent-shelter-distances) shelter-
nodes)
    set destination shelter-dest-node

    let path []
    let individuals-on-path []
    nw:set-context nodes roads

```

```

let dest-node destination
;set current-node one-of nodes with-min [distance myself]

ask home-node [
  set path nw:weighted-path-to dest-node weight
  set individuals-on-path nw:turtles-on-weighted-path-to dest-node weight]

set travel-path individuals-on-path
;set agent-state 3
if travel-path = FALSE Or travel-path = 0
  [set agent-state 9 stop]

set travel-path-total travel-path
]
end

to calculate-path-home
ask households [
  let path-home []
  let individuals-on-path-home []
  if home-node = nobody [set color red set status-report ["Home destroyed. Staying in shelter..."] set
agent-state 9 stop ]
  if destination = nobody [ set color red set status-report ["Stuck in shelter..."] set agent-state 9 stop ]
  if destination = 0 [ stop ]
  let dest-node home-node
  ask destination [
    set path-home nw:weighted-path-to dest-node weight
    set individuals-on-path-home nw:turtles-on-weighted-path-to dest-node weight]
  set travel-path-home individuals-on-path-home

;set agent-state 3
if travel-path-home = FALSE Or travel-path-home = 0
  [set agent-state 9 stop]

set travel-path-home-total travel-path-home]
end

```

```

; ----- Node (road) related -----

to damage-to-nodes
  ask nodes [if risk-zones-class = 3 And random 100 < 10 [ ask patch-here [set road-dmg road-dmg + 1]
  die ]] ;probability of 10 percent
  ask nodes [if risk-zones-class = 2 And random 100 < 3 [ ask patch-here [set road-dmg road-dmg + 1] die
  ]] ;probability of 3 percent
  ask nodes [if risk-zones-class = 1 And random 100 < 1 [ ask patch-here [set road-dmg road-dmg + 1] die
  ]] ;probability of 1 percent
end

; ----- Patch-related -----
; ----- Counters and preparations for output creation -----
-

to count-households-1
  if count households-here > 0 [
    set counter-phase1 (counter-phase1 + 1)
  ]
end

to count-households-2
  if count households-here > 0 [
    set counter-phase2 (counter-phase2 + 1)
  ]
end

to count-shelter-1 ; also possible: ask shelters [ ask closest-node [ ask patch-here [ set
shelter-counter-1 count-households-here]]]
  ask patch 68 80 [
    set shelter-counter-1 count households-here]
  ask patch 24 96 [
    set shelter-counter-1 count households-here]
  ask patch 62 80 [
    set shelter-counter-1 count households-here]
  ask patch 56 30 [
    set shelter-counter-1 count households-here]

```

```

ask patch 30 104 [
  set shelter-counter-1 count households-here]
ask patch 29 88 [
  set shelter-counter-1 count households-here]
ask patch 48 75 [
  set shelter-counter-1 count households-here]
ask patch 22 144 [
  set shelter-counter-1 count households-here]
ask patch 35 109 [
  set shelter-counter-1 count households-here]
end

```

```

to count-shelter-2 ; also possible: ask shelters [ ask closest-node [ ask patch-here [ set
shelter-counter-2 count-households-here]]]
ask patch 68 80 [
  set shelter-counter-2 count households-here]
ask patch 24 96 [
  set shelter-counter-2 count households-here]
ask patch 62 80 [
  set shelter-counter-2 count households-here]
ask patch 56 30 [
  set shelter-counter-2 count households-here]
ask patch 30 104 [
  set shelter-counter-2 count households-here]
ask patch 29 88 [
  set shelter-counter-2 count households-here]
ask patch 48 75 [
  set shelter-counter-2 count households-here]
ask patch 22 144 [
  set shelter-counter-2 count households-here]
ask patch 35 109 [
  set shelter-counter-2 count households-here]
end

```

; ----- GIS-related -----

```
to setup-paths-graph
  set-default-shape nodes "circle"
  let node-precision 5
  foreach polylines-of roads-data node-precision [ ?1 ->
    (foreach butlast ?1 butfirst ?1 [ [??1 ??2] -> if ??1 != ??2 [ ;; skip nodes on top of each other due to
rounding
      let n1 new-node-at first ??1 last ??1
      let n2 new-node-at first ??2 last ??2
      ask n1 [create-road-with n2]
    ] )
  ]
  ask nodes [ set color cyan set size 0.5]
  ask nodes [hide-turtle]
end
```

```
to weighted-distance
  foreach sort roads [ the-road ->
    ask the-road [ set weight link-length ]
  ]
end
```

; ----- Output creation -----

```
to data-output
  ask patches [
    set road-usage-phase-1 gis:patch-dataset counter-phase1
    set road-usage-phase-2 gis:patch-dataset counter-phase2
    set shelter-phase-1 gis:patch-dataset shelter-counter-1
    set shelter-phase-2 gis:patch-dataset shelter-counter-2
    set damaged-roads gis:patch-dataset road-dmg
  ]
end
```

```
set road-usage-1-output "outputfiles/road_usage_phase1.asc"
gis:store-dataset road-usage-phase-1 road-usage-1-output
```

```
set road-usage-2-output "outputfiles/road_usage_phase2.asc"
gis:store-dataset road-usage-phase-2 road-usage-2-output
```

```
set shelter-phase-1-out "outputfiles/shelter_phase1.asc"
gis:store-dataset shelter-phase-1 shelter-phase-1-out
```

```
set shelter-phase-2-out "outputfiles/shelter_phase2.asc"
gis:store-dataset shelter-phase-2 shelter-phase-2-out
```

```
set dmg-roads-output "outputfiles/road_damage.asc"
gis:store-dataset damaged-roads dmg-roads-output
end
```

; ----- Reporter functions -----

```
to-report polylines-of [dataset decimalplaces]
  let polylines gis:feature-list-of dataset
  set polylines map [ ?1 -> first ?1 ] map [ ?1 -> gis:vertex-lists-of ?1 ] polylines
  set polylines map [ ?1 -> map [ ??1 -> gis:location-of ??1 ] ?1 ] polylines
  set polylines remove [] map [ ?1 -> remove [] ?1 ] polylines
  set polylines map [ ?1 -> map [ ??1 -> map [ ???1 -> precision ???1 decimalplaces ] ??1 ] ?1 ] polylines
  report polylines
end
```

```
to-report new-node-at [x y]
  let n nodes with [xcor = x and ycor = y]
  ifelse any? n [set n one-of n] [create-nodes 1 [setxy x y set size 0.5 set n self]]
  report n
end
```

```

to-report meters-per-patch
  let world gis:world-envelope
  let x-meters-per-patch (item 1 world - item 0 world) / (max-pxcor - min-pxcor)
  let y-meters-per-patch (item 3 world - item 2 world) / (max-pycor - min-pycor)
  report mean list x-meters-per-patch y-meters-per-patch
end

```

```

to-report shelter-locations
  let shelters-loc []
  foreach gis:feature-list-of shelters-data [ ? ->
    set shelters-loc lput (gis:location-of (first (first (gis:vertex-lists-of ?)))) shelters-loc
  ]
  report shelters-loc
end

```

```

; schedule reporter

```

```

to-report model-phase-monitor
  let output []
  if model-phase = 999 [set output "Setup complete. Ready to create agents..." ]
  if model-phase = 998 [set output "Agents created. Ready to start simulation..." ]
  if model-phase = 0 [ set output "Event 1 Evacuation proceeding..." ]
  if model-phase = 1 [ set output "Population in shelters. Event 1 in process..." ]
  if model-phase = 2 [ set output "Event 1 over... Population returning home..." ]
  if model-phase = 3 [ set output "Post event 1 / Pre-event 2..." ]
  if model-phase = 4 [ set output "Event 2 Evacuation proceeding..." ]
  if model-phase = 5 [ set output "Population in shelters. Event 2 in process..." ]
  if model-phase = 6 [ set output "Event 2 over... Population returning home..." ]
  if model-phase = 7 [ set output "Post event 2. Simulation complete..." ]
  report output
end

```